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Effects of drought and vegetation management on the establishment of three tree species in Northamptonshire, England.

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ABSTRACT

Water is a limiting factor in the distribution and growth of trees. Changing climatic conditions are likely to significantly effect tree species development. The planting and establishment of trees needs to take into account these changing factors in terms of design and species selection. This study looked at survival and growth of newly planted trees under field scale conditions and the effects of soil water availability and ground treatments. The experiment followed a blocked plan allowing a line source design to irrigate three tree species, ash, Douglas fir and oak. Each plot of 90 trees was divided into 5 irrigation subplots with varying levels of water application. Two ground treatments, bare ground and vegetated were also applied. Over a three year period, there was a significant effect of species (P<0.001) and herbicide application (P<0.01) on tree survival. Tree height and diameter were significant (P<0.01) between species and herbicide. Irrigation had a significant effect on growth rates of all species with no effect on survival. Ground vegetation biomass significantly increased in high irrigation subplots (P<0.01), with increasing festuca rubra dominance decreasing plant diversity (R^2=0.8533). The results suggest that soil moisture availability increases tree growth but does not significantly improve survival rates of the tree species studied. Water is a key factor in the establishment of trees with maintained soil moisture increasing growth development of individuals. Therefore site and species selection are essential in the design of woodland plantings for conservation, recreation and commercial activities.

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SYMBOLS AND ABBREVIATIONS

DEFRA	Department of Environment, Food and Rural Affairs	
SWD	Soil water deficit	(mm)
ANOVA	Analysis of variance	
UKCIP	UK Climate Impacts Programme	

NOTE ON STATISTICAL ANALYSIS

1. Deference between treatments were assumed to be statistically significant at or below a 5% level of probability ($p \leq 0.05$).

1 INTRODUCTION

This chapter introduces the rationale for the thesis and describes its aims, objectives and structure.

1.1 Rationale

Newly planted woodlands have become an integral part of the British landscape. Since 1988, the Woodland Grant Scheme and Farm Woodland Premium Scheme (FWPS) in 1992, have encouraged tree planting and reforestation of farmland in England. In 2005, this was superseded by the England Woodland Grant Scheme (EWGS) in 2004, however the process of grant funding for tree planting has largely remained the same. Traditionally native deciduous species have been planted for conservation (Helliwell, 1984), and exotic species for timber production. However a more multi-purpose approach that encompasses landscape, environmental and economic forestry requirements has been promoted by this new funding criteria.

European woodlands covered much greater land areas than they do today (Magnus *et al.*, 2004). In Britain this has increased from 4% of land cover in 1918 to 8% today. However size and species have continually changed in many of these sites. There is a willingness, across Europe, to maintain and replant much of this lost forest cover. For example Magnus *et al.* (2004) identified restoration activities in Denmark, which aims to double the forested area within one generation.

Water availability is a major factor affecting the distribution and growth of tree species in the UK (Hall & Roberts, 1990). Water being key factors in the Photosynthetic and transpiration processes (van der Meer *et al*, 2002). This reduction in water has implications in terms of species selection for the reforestation schemes across the country for both conservation and commercial activities. With an increased demand for water resources the possible effects of woodland development on groundwater recharge could significantly affect other high water demanding activities such as housing and agriculture. In addition the potential effects of a changing climate, in terms of seasonal precipitation, temperature rises and transpiration rates could have far reaching impacts on UK forestry. The availability of water resources may eventually affect woodland design and species selection.

There has been little field research on the effects of tree-water relationships, including irrigation, in the establishment and development of broadleaved species (Meiresonne, 1999). The irrigation of large-scale plantations in England is uneconomic because of the low value of timber. However studies carried out in the USA (Kramer, 1987) have shown the benefits of irrigating individual urban trees.

This experiment was undertaken over a three year period from March 2001 to December 2003, whilst the author was employed full-time as a lecturer at Moulton College. Due to work pressures, the amount of time that the author could spend on the project was limited.

1.2 Aim

The overall aim of the work was to understand the interactions between water availability and the development of new woodlands from a production and ecological perspective.

1.3 Structure

This thesis is divided into nine chapters. The second chapter is the literature review. This is followed by a description of the site (Chapter 3), and the imposition of treatments (Chapter 4) and the tree responses (Chapter 5) during the first two years. During the third year, a significant irrigation treatment was applied, and this is described in Chapter 6, along with tree responses (Chapter 7) and vegetation responses (Chapter 8). The final chapter (Chapter 9) synthesises the results.

2 LITERATURE REVIEW

This chapter attempts to describe the importance of water relations on the growth and development of new woodlands. It firstly reviews tree responses to the environment, the effect of soil water status on tree succession and the potential effects of climate change. The effect of ground vegetation has been consistently highlighted as a factor affecting tree growth and the process of early woodland succession is described. Lastly the reasons for selecting the specific tree species used in the experiment are described.

2.1 Tree responses to the environment

Yield and light

Monteith (1977) showed that light interception can determine potential crop yields, which can be related to the interception of solar radiation; the efficiency with which that intercepted radiation is used to produce dry matter; the proportion of dry matter which forms the 'economic yield'. Assuming plants (including trees) can gain adequate water and nutrients, the potential biomass production is determined by the light intercepted by the canopy. Cannell *et al.* (1989) suggests "*that the amount of dry matter produced by a plant stand is linearly related by the amount of light energy intercepted by the foliage canopy*".

Cannell *et al.* (1989) and Corley (1984) have used simple models to relate the total biomass (above and below ground) accumulated by a tree over a season to the amount of intercepted light. Cannell *et al.* (1989) showed that by understanding how plants functions, models could be established to determine potential and actual crop yields. In turn, these can be related to differing water applications. This allowed the process of wood production to be identified, plus it enables decisions of how yield may be controlled by climate, weather and management (Cannell *et al.*, 1989). Although Cannell used this model for estimating actual or potential yields in willow and poplar stands, the equations may provide reliable estimates for slower growing trees such as the species identified for this research.

Yield and soil water availability

The link between production of dry matter and plant water use has been shown in several studies. In relation to trees, it has focussed on relatively fast growing species such as willow (*Salix*) and poplar (*Populus*) (Souch & Stephens, 1997) or on established stands of commercial tree species (Aranda & Pardos, 1996; Anekonda Adams, 2000). Modelling tree growth in relation to the environment is a complex problem (Tewari, 1999). Davies *et al.* (1987) suggested that water deficiency can have an immediate effect on leaf growth, and suggests information on canopy and leaf area development needs to be related to environmental factors such as water availability (Davies *et al.,* 1989). Anekonda & Adams. (2000) highlighted that summer drought was a major factor on growth rate of Douglas fir (*Pseudotsuga menziesii*) in their studies. Zier (2003) reported that drought was the primary mechanism in forest decline. Cannell *et al.* (1989) and Kozlowski (1982a) states that waterlogging can also reduce growth rates.

Water use is significantly reduced in droughted plants, with the most obvious short-term effect of water stress being stomatal closure (Corley, 1986). This induced closure of the stomata will limit water loss, thus lowering plant stress. However, this will also reduce carbon dioxide uptake for photosynthesis (Corley, 1986). Souch and Stephens (1997) showed a reduction of 65% in water use by poplars in severe drought treatments when assessed against high water availability treatments.

Studies on Norway spruce (*Picea abies*) by Cienciala *et al.* (1994) discussed the effects of water availability on the growth and transpiration of this species under different water regimes. Fuhrer (1988) noted the relationship between drought and oak (*Quercus* sp.) decline, and emphasised the inter-relationship with pathological responses. This study again examined mature trees over one growing season. Studies by Clark and Kjelgren (1990) and Kramer (1987), on urban trees, identified that mature, or established, trees have a greater ability to tolerate water stress that newly planted specimens. They highlighted the need for individual tree irrigation during early establishment in urban environments.

Water availability

The actual transpiration by a tree stand will in part depend on the availability of water within the ground (Grote & Pretzsch, 2002). Souch and Stephens (1998) and Mahoney and Rood (1992) have established relationships between water availability and tree growth in short rotation species such as poplar. Veihmeyer and Hendrickson (1931) suggested that water would be available to plants from all soil water ranges, field capacity to permanent wilting point. Penman and Pierce provided a line between the two (Batchelor, 1984).

Cienciala (1994) showed that intensive growth in Norway spruce (*Picea abies*) corresponded closely with high water infiltration, and suggested that transpiration is limited below a certain level of soil water. The same hypothesis was suggested by Granier *et al.* (1999) for forest stands, in that transpiration is reduced in accordance with stomatal closure under water stress. However, changes in temperature and or water resources will have impacts on the forest ecosystems as a whole (Moffat, 1999) affecting nutrient cycling, diseases and pests on timber species and native species of wildlife. This has been highlighted in tree ring studies focusing on summer radial growth. Positive precipitation and negative temperature responses have been suggested for the variation in ring size (Gonzalez, 2001). Therefore dendrochronological studies have allowed the study of climate change and the effects on the biological environment.

Moffat (1999) reported that the yield class of ash (*Fraxinus excelsior*) was insensitive to changes in soil water deficit, whereas the yield class of oak (*Quercus petraea* & *Q robur*) was reduced at high and low deficits. The same study suggested that the yield class of ash is increased by high temperatures, whereas the yield class of oak is unaffected. The yield class of Douglas fir (*Pseudotsuga menziessi*) was predicted to be sensitive to both temperature and soil moisture deficit (Moffat, 1999). In a study by Girona *et al.* (2002) reviewing evapotranspiration rates in peach trees they noted the importance of wetting patterns and soil moisture at depth. Costello *et al.,* 2005 noted that providing deep root irrigation compared to surface irrigation enabled better growth responses.

Ground vegetation

Competition from herbaceous species can seriously affect the early establishment of planted trees (Groninger *et al.,* 2004). The study of growth units in *Quercus petraea*, by Chaar *et al.* (1997) showed that grass competition reduced growth of seedlings. There is competition for resources such as nutrients and water and Smith *et al.* (2002) also refers to allelopathic responses. Therefore, strategies for the control of ground flora species has become an integrated part of tree establishment (Watt *et al*., 2002) and a requirement under a range of grant funding criteria. Controlling weed development can instigate higher early growth rates in trees providing better access to resources such as nitrogen, water and light (Watt *et al*., 2002). This can be particularly apparent with woodland plantings of agricultural fields, leading to reduced growth rates by residual agricultural ruderal species (Willoughby & McDonald, 1999).

Forestry Commission and ADAS experiments, (especially on inter-row management) on farm woodlands found that the sowing of grassland mixes between tree rows enhanced conservation diversity (Willoughby & McDonald, 1999). Willoughby & McDonald (1999) also suggested that the maintenance of completely weed free environments would maximise tree growth, but this can be costly and often impractical. The imposition of such systems will significantly reduce the conservation value of a site especially if the primary reason for planting is to enhance the ecological status of the area. Agroforestry advocates the growing of crops alongside trees, however it suggests that established trees will utilise water and nutrients below that exploited by crop roots (Orig *et al*, 1991). On the other hand the no weed management is highly likely to significantly reduce tree growth and survival (Willoughby & McDonald, 1999). The management of herbaceous species in tree plantations needs to be carefully designed and may have important implications on development and timing of canopy closure on the site (Groninger *et al*, 2004). Britt and Smith (1997) support the requirement to provide good weed control, with the most commonly used “foliar acting chemical glyphosate and less frequently a residual herbicide” (Britt and Smith, 1997). By maintaining good growth rates this will minimise the length of time needed for ground vegetation management (Burgess, 1996).

Groninger *et al.* (2004) evaluated how trees, specifically with *Fraxinus pennsylvanica,* responded to vegetative competition,. The development of models for field layer interaction in woodland in secondary woodland plantations and experimental plots have been utilised by Hooley & Cohn (2003). Research into community response to disturbance is most often applicable to large natural areas rather than a single experimental site. This presented a model of the colonisation from residual seed banks and the role of inhibitor species in the re-emergent flora. Grime *et al.* (1989) first described the role of individual plants and the presence in vegetation communities using the Competitor-Ruderal-Stress (C-R-S) model, highlighting the different strategies adopted by plants to exploit niches. This can be related to ground vegetation development, especially ruderal communities, but also to tree colonisation and successional developments.

Competitive advantage of trees may also be restricted by ground vegetation competing for similar water resources. Strong weed growth especially on lowland sites with limited water availability has been shown to compete with tree species for soil moisture (Britt, 1999). In contrast competition is often less in upland sites with increased rainfall (Britt, 1999). Changes in ground vegetation species, due to climate change, may also pose similar problems in competition for water resources, compounding any stresses from restricted water levels. The understanding of the effects of ground vegetation on establishing trees and woodlands is vital to these applied studies. Which in turn may provides guidance to the early management of plantings.

2.2 Succession

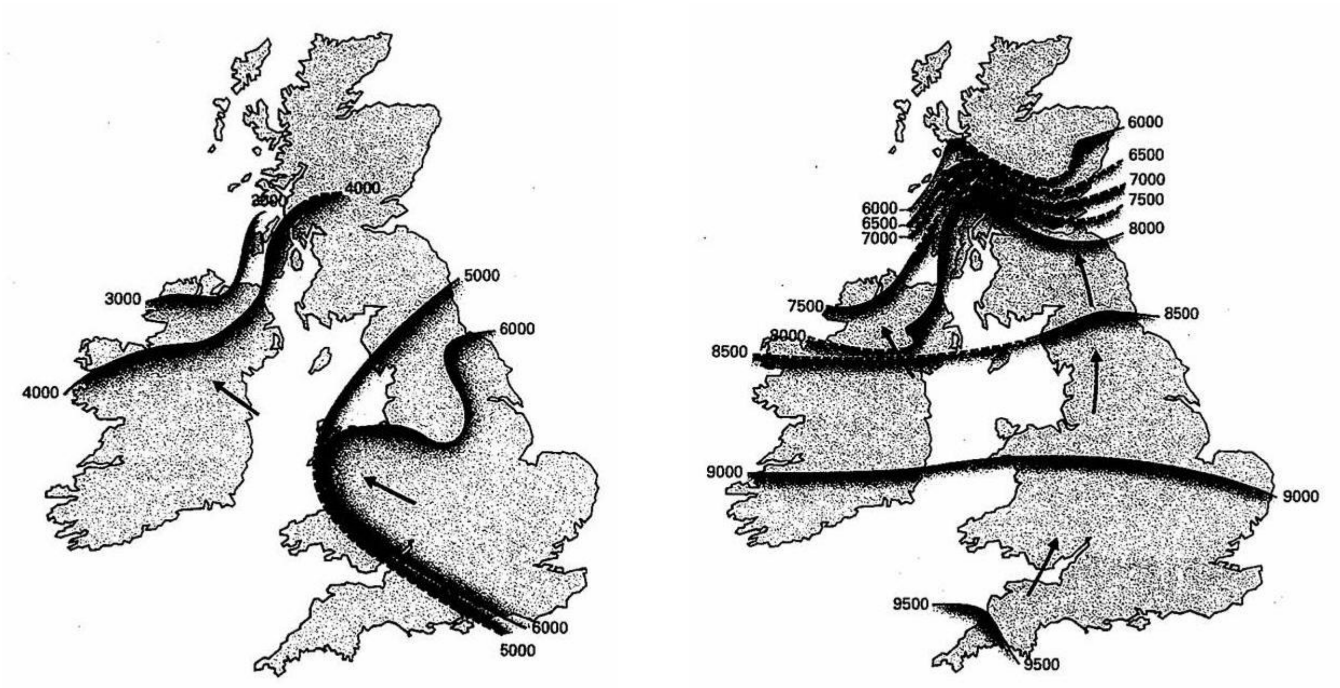
There are many factors that control the natural distribution of plant species (Moffat, 1999). Climax vegetation development is closely related to the climate (Packham *et al.*, 1992), and climate controls the distribution of woodland types in Europe (Watson *et al.,* 1995). However Moffat (1999) suggests that as most native trees found in Britain are also present across Europe under what can be different climatic conditions, climate change is unlikely to change their suitability as a species. Although local, regional and national province may be significantly affected (Stewart *et al.*, 2006).

Soil water availability may have implications for the natural succession of woodland. As colonising species invade open environments, the sequences that allow other species to develop and control change may related to the availability of soil moisture which changes with the development of woody plant communities. When planting mixtures of tree species some particular species may have a competitive advantage in terms of water use. The growth of ground vegetation will control water movement through the soil profile, therefore a need to manage understorey growth is important for initial establishment and long term development of trees.

Vegetation communities can change rapidly through many successional seres if anthropogenic and environmental factors permit. Natural developments are closely linked to plant interactions and the control of previous vegetation communities (Sprugel, 1991). Therefore under simulated conditions such as woodland plantations, the underlying vegetation can influence the development of individuals and species. However if optimum growing conditions are maintained (naturally or artificially), their adverse effects of vegetation competition can be, to some degree, negated (Groninger *et al.,* 2004).

2.3 Climate change and tree growth

Climate change has been the main controlling factor in successional changes and variations in woodland cover throughout the history of the Britain (Packham *et al.* 1992). The changes in woodland type over the last 5000 years have been widely documented, identifying changes in wildwood provinces through pollen profiles from all over the British Isles (Rackham, 1981). Changes in individual species abundance have been closely linked to these climatic shifts (Milner, 1992). The analysis of pollen samples has provided evidence of species movement from continental Europe through Britain (Figure 2.1). Oak colonised the British Isles in a northerly direction, whereas ash displayed a more lateral movement from east to west (Figure 2.1). This helps explain how tree species are effected by climatic change.



a) Ash b) Oak

Figure 2.1. Isochrone contour maps for a) Ash and b) Oak. Based on pollen analysis, the lines represent the limit (before present) to which these tree species have spread across the British Isles over time. (reproduced from Milner, 1992).

Although there is still debate about the importance of human factors on these changes (Dalezios *et al*, 2000), it has been shown that the climate is becoming warmer and this will have important implications for the ecology and production of woodlands. The management of forests will need to adapt practices to these future climate changes which are likely to be characterised by extreme weather events (Bodin, 2007).

The existing record of weather measurements is generally considered to be not long enough to give a long-term picture of climatic variability (Jones *et al.,* 2001), and that records have already been influenced by anthropogenic factors (Jones *et al.,* 2001). However, Stern (2006) suggested that the concentration of greenhouse gases in the atmosphere is predicted to double pre-industrial levels by 205). This could increase the global average temperature by $2^{o}C$ (Stern, 2006). More extreme predictions suggest that temperature rise could exceed $5^{o}C$ in the long term (Stern, 2006).

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In the 1990s, the average January-March temperature was 5.6°C, compared with 4.3°C in the 1980s (Sparks, 1999). This shows an average change of 1.3°C between these dates, with the 1990s now the warmest decade on record (Sparks, 1999). To what extent these changes can be attributed to any specific causes (Osborn *et al*, 2000) is debatable, however the balance of opinion points to these changes being at least partly due to human activity, with predications of a further 2°C over the next century (Sparks, 1999).

These changes are inevitably going to influence woodland development in the future, for example early bud opening (phenology), with an increase in temperature, rise in water stress (too much or too little) and an increase in herbivore activity (Fuhrer, 1998). Major organisations such as English Nature and DEFRA have now recognised the potential effects on both native and commercial crops. There could also be the potential to increase the range of commercial species grown in the UK, and increasing the performance of existing species. However this may not necessarily be seen as a positive factor, certainly from a conservation perspective, if native or traditional crop trees decline. Natural tree species change has been identified as evidence of warmer temperatures. Gamache & Payette (2004) studied the expansion of boreal forest vegetation in northern Quebec showing growth-climate relationships in black spruce (*Picea mariana*). This showed a complex association with warmer summer temperatures and increased CO_2 levels. The latter is a factor, which is now considered significant in assessing climate change and plant interactions

Climate changes are dynamic in nature (natural or human induced) and possible rainfall changes in England, with associated effects of different levels of water stress may control future relative survival, growth, and determine species dominance. This could have major implications on the natural development of woodlands, but especially areas of trees being planted under various grants and incentives. This has led to serious concerns on the impact of these changes on the forestry industry throughout northern Europe (Fuhrer, 1998). Although the amount of annual rainfall did not change throughout the 20th century the evidence suggests that the winters became wetter and the summers became drier (Hopkins, 2007). This could have key implications on the survival and development of planted trees (Merryweather, 2007).

Concern over climate change, especially precipitation and temperature, has not been a recent factor in terms of forestry practices. Lines in 1973 and Cannell *et al.* in 1989, all suggested that changes in species selection may be needed due to changes in growing conditions. Cienciala (1994) and Moffat (1999) have also raised these concerns. Changing climatic conditions, which may, as trends suggest, become more dramatic due to anthropogenic factors are more likely to lead to exaggerated change over much quicker time periods than previously, with more significance on plant growth (Saxe *et al*, 2001). The effect on England's semi-natural woodlands, especially with species at the limits of their ecological range (Broadmeadow, 2001) will be significantly affected considering the speed which these changes seem to be occurring.

Reductions in water resources, in contrast to temperature increases, are likely to have major effects on the growth rates of some tree species (Moffat, 1999). Southern areas of the country would be at greater risk from reductions in water due to already limited precipitation, especially in regions such as East Anglia (Hall & Roberts, 1990). Moffat (1999), Saxe *et al* (2001) and Gamache & Payette (2004) suggest that it is unlikely that species would decline dramatically or die, however a decline in the fecundity of some species would be expected. Moffat (1999) suggested that growth rates in species such as oak would be affected, whereas ash would be unaffected by changes in moisture deficit. However this was from a viewpoint of mature trees rather than recently-established plants. The complex ecological relationships within any biological system make it difficult to understand how climate change may affect UK forestry (Broadmeadow, 2001). For example Fuhrer (1998) related the incidence of oak decline to an intensification of tree pest and diseases linked to climatic change.

Much of the recent tree planting has been promoted under the banner of 'climate change' as carbon sinks, however long term tree survival, in many cases, has not seemed to be a factor in the decision making of sites and or species. The Forestry Commission (2001) highlighted that the effects of changing climates are likely to affect all aspects of woodland management, effecting individual tree species and woodland use as a whole. A better understanding of how this may affect plant growth has been reported by van der Meer *et al* (2002), suggesting the doubling of CO_2 levels would increase plant growth through carbon assimilation and transpirational water loss. Photosynthetic rates would also be effected by temperature affecting plant growth (van der Meer *et al*, 2002) and respiration and transpiration rates differently at different latitudes (Andalo *et al*, 2005; Hopkins, 2007). There would seem a positive element to planting of trees, taking account of these environmental changes and is vital for the long-term woodland management (Forestry Commission, 2001). The key areas suggest were;

- Where a species is already on the limit of its moisture range, it should not be planted.
- Changes to grant schemes offered by the government may be necessary.
- Mixed planting of native species should be encouraged to increase success of continuing woodland cover.
- Aspiration of planting only native species should be considered carefully if it is not critical on conservation grounds.
- Consideration to the use of more southerly provenances of native species in appropriate circumstances.
- Habitat Action Plan targets for beech/yew native woodland will not be actively pursued in the East of England.
- Species must be matched to site conditions now and in the future.

As a mitigation to control climatic effects, and to replace the loss of natural forests, Stern (Stern, 2006) suggested these activities could be highly cost effective.

The impacts on a national or regional scale are likely to be more difficult to predict (Merryweather, 2007). These uncertainties at a regional and even local scale (Bodin, 2007), will present a range of challenges to all land managers. Data has show that over the 20th century the mean temperature in central England has risen by 1^{o}C (Hopkins, 2007). Within central and eastern regions this could have significant long-term implications on forestry (Hall & Roberts, 1990).

The IPCC (2001) have identified the potential impact on the East Midlands as increased temperatures, evaporation and reduced rainfall patterns. Woodlands would be affected by increased drought conditions especially in the East of England region (IPCC, 2001).

Under these scenarios woodland planting needs to be much more precise in terms of species selection and location if good survival and growth rates are to be attained in these areas. It is clear that care and agreed management is required to attain this

(Merryweather, 2007) and having a greater understanding of climatic forces on trees species is required.

2.4 Tree species choice

Many species provide an important component of mixed broadleaved woodlands in Britain (Stewart *et al.*, 2006). The objective in deciding on the appropriate species to include in this project focussed on a group of commonly-used species which could show a varied ability to respond to environmental stress. Oak and ash were considered to show different responses to drought and temperature (Moffat, 1999) whilst Douglas fir is a commonly planted coniferous species. The development of deciduous and coniferous saplings differs, especially between environmental parameters (Gotmark *et al,* 2005). However water availability in this early developmental stage has not been significantly studied, and research has favoured individual species (Adalo *et al*, 2005; Stewart *et al*, 2006; Souch & Stephens, 1997), rather than experiments incorporating mix species selections.

Ash

Ash (*Fraxinus excelsior*) can be found distributed throughout the north temperate zone in Europe and Asia, and in parts of Africa (Savill, 1992). Ash tends to grow most successfully on calcareous soils which are fertile and well drained (Rodwell, 1991), which is often contrary to the view of ash occupying damp valley bottoms (Savill, 1992). It is an important component of mixed broadleaved woodlands in Britain (Rodwell, 1991), and it is also one of the major commercial broadleaved tree species planted in Britain (Kerr & Cahalan, 2004). Savill (1992) suggest that very little work has been carried out in Britain on selecting quality ash trees, or distinguishing between ecotype, for propagation purposes. However this has been somewhat addressed with the development of the European-wide Fraxigen Project (Stewart *et al.,* 2006). Moffat (1999) describes ash as a robust relatively quick growing species with predicted yield class increases with a rise in temperature.

Oak

The two native species of oak found in Britain, *Quercus petraea* and *Q. robur* occupy different ranges in natural distribution although there is some overlap (Peterkin, 1993).

Sessile oak (*Q. petraea*) was chosen for this project, due to its preference as a forestry species for its more upright straight form (Rodwell, 1991). Although Savill (1992) identifies that the pedunculate oak *(Q. robur*) seeds more freely and the acorns are often easier to store. For both species many plantations are outside their natural range and environmental requirements which may often lead to poor growth and economic productivity. Evidence suggests that the growth of this species may be susceptible to reduced water supply (Moffat, 1999).

Douglas fir

Douglas fir *(Pseudotsuga menziesii)* was the only non-native species within the study and the only conifer. Although the species has been planted for commercial purposes throughout much of Britain the preferred sites are to the wetter western parts of the country (Savill, 1992). The experimental site provided alternative conditions to these preferred locations. Moffat (1999) indicated that a temperature rise may improve yield class in this species, but reduced soil moisture may negate these increases.

2.5 Conclusions

Much of the work carried out on yield projections for woody species has been developed around relatively fast growing species such as willows and poplars. Studies on more traditional coniferous or broadleaved trees have focused on existing mature forestry stands (Granier *et al.* 1999; Cienciala *et al.*, 1994), often discussing water relations over one growing season. However, Granier *et al.* (1999) identified the need for large-scale long-term studies between climate interactions, hydrology and forest management. They proposed a water model to address drought events affecting growth in various trees species over long-term period (Granier *et al.,* 1999).

With the predicted changes in climate, it is unclear at present which changes are likely to increase or reduce growth rates and yield. At specific sites, water resources will play a major factor in species selection and determine the suitability of existing native species in the formation of new woodlands (Moffat, 1999). Future forests are likely to be comprised of species mixtures not necessary found today (Watson *et al,.* 1995). This research aims to understand the interactions between water availability and the development of new woodlands from a production and ecological perspective. This is essential to inform continued forest cover for both timber production and conservation planting (Watson *et al.,* 1995). The Forestry Commission along with many conservation organisations have promoted the planting of native species (Brown, 1997), which are considered the most appropriate for their ecological value and environmental requirements. With such a prospect of, if not already occurring, rapidly changing environment, this policy could limit the survival capabilities of our woodlands. As highlighted by Charles Notcutt in the opening remarks of the Trees in a Changing Climate conference "*given that trees planted now in a climate that is changing at an accelerating rate will come to maturity in a very different climate than we are currently experiencing*". Should we consider planting species (native or introduced) which will be capable of functioning (growth, reproduction) under these altered conditions?

2.6 Objectives

The stated aim of the research was to improve our understanding of the interactions between water availability and the development of new woodlands from a production and ecological perspective. It focussed on the traditional plantation crops of ash, Douglas fir and oak. It also focuses on the interrelationships between the tree species and the understorey vegetation, both in terms of production and conservation value. The specific objectives are:

1. To determine the responses of oak (*Quercus petraea*), ash (*Fraxinus excelsior*) and Douglas fir (*Pseudotsuga menziesii*) to water availability.
2. To determine the responses of oak, ash and Douglas fir to the removal of competing vegetation.
3. To determine the interactions between the above.
4. To determine the interactions between tree species and floral diversity.

3 MATERIALS AND METHODS

This chapter describes the experimental site, and the establishment of the trees for the experiment.

3.1 Site description

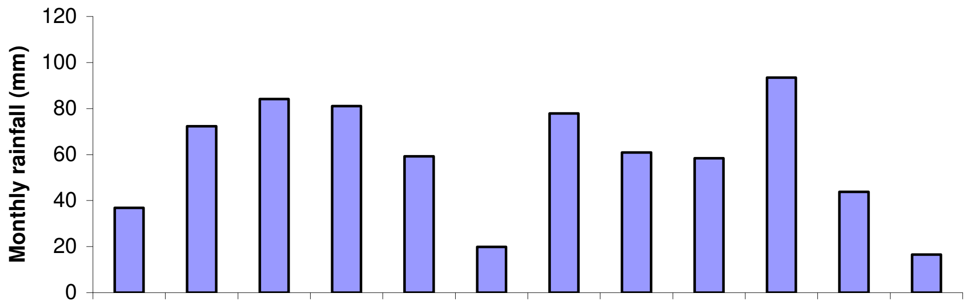
Moulton College is located north of Northampton in Northamptonshire (52°17’39.25” N 0°51’27.97” W). The College owns 436 ha, consisting of a mixed arable and livestock farm. After various attempts of finding a suitable site, the southern end of Castle Hill field (Figure 3.1), was identified as a suitable area. The chosen experimental site was selected due to having good access with available mains water, homogeneous soil type across the plot, and no obstructions e.g. overhead cables or close proximity of buildings. There is a slope at the site being highest in the West and lowest in the East. The effect of the slope is discussed further later in this chapter.

Figure 3.1. Aerial photograph showing the Holcot Centre of Moulton College and the position of the experimental site, enclosed in white rectangle (Image taken from Multi-map.com).

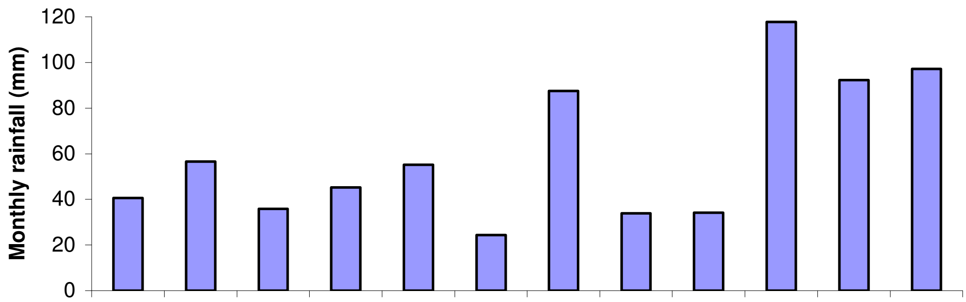
3.2 Meteorological data

Meteorological data was collected from Pitsford School, who manage an automatic weather station approximately 3 km from the experimental site. Monthly rainfall was calculated (Figure 3.2). The annual rainfall ranged from 704.1 mm in 2001, to 720.5 mm in 2002 and 482.0 mm in 2003.

a) Rainfall 2001



b) Rainfall 2002



c) Rainfall 2003

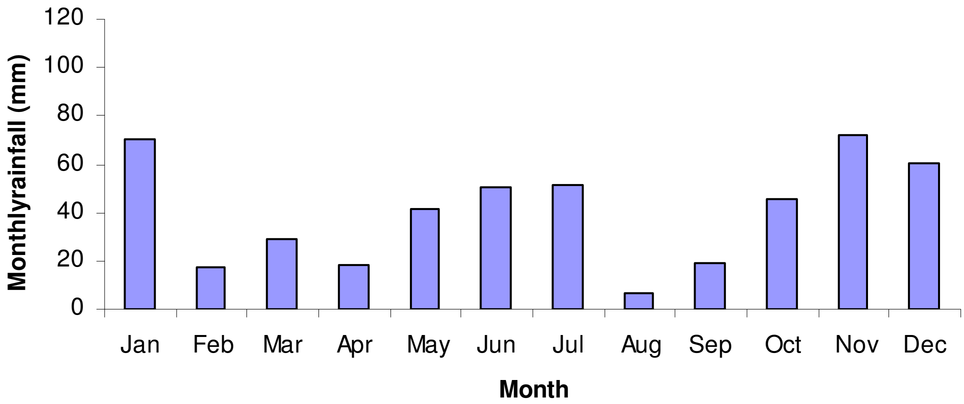
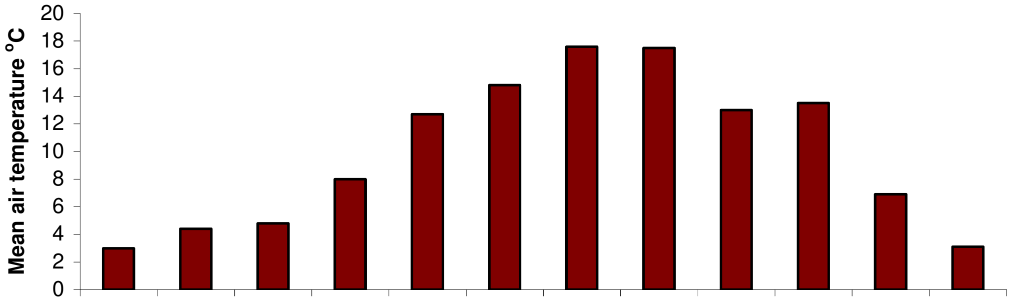


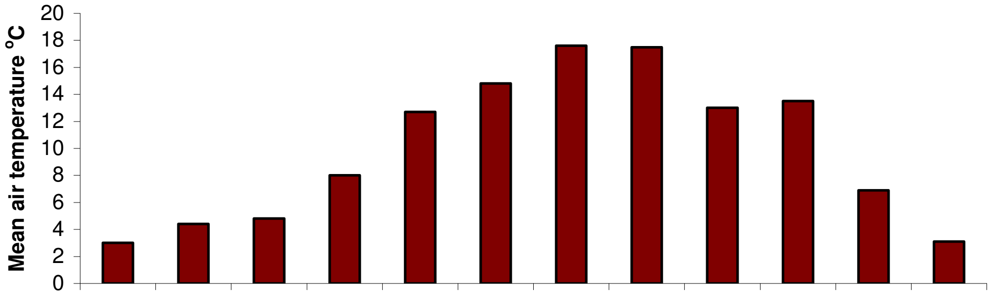
Figure 3.2. Monthly rainfall for Pitsford, Northamptonshire, for 2001, 2002 and 2003. showing changes in rainfall between months and years.

Monthly mean air temperature was calculated (Figure 3.3). The average temperature between April to September ranged from 13.9 ^{o}C in 2001, to 14.3 ^{o}C in 2002 and 15.2 ^{o}C in 2003.

a) Temperature 2001



b) Temperature 2002



c) Temperature 2003

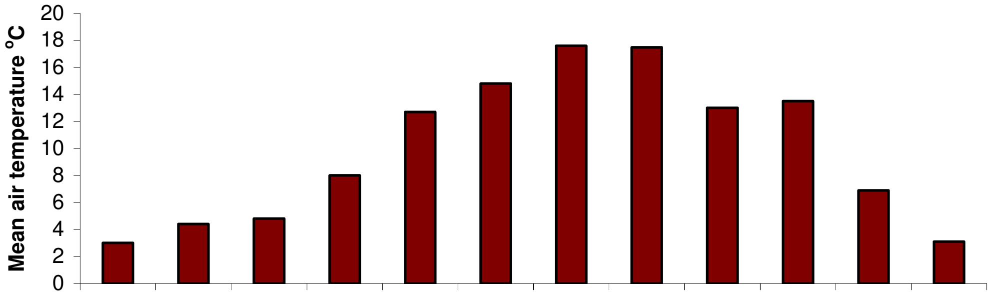


Figure 3.3. Monthly temperature for Pitsford, Northamptonshire, for 2001, 2002 and 2003. showing changes in temperature between months and years.

3.3 Soil type

In early 2001, two initial soil pits were dug to a depth of 50 cm at the experimental site prior to the planting of the trees. These suggested that the soil type was broadly consistent between the two points.

3.3.1 Soil water release curve

To identify the soil type and the potential for water movement within the soil profile soil samples were taken at a depth of 100 mm to create a soil water release curve. Due to the slope of the experimental area, three replicates were taken from three points throughout the site (blocks 1, 2, 3 and 4), to allow consistency to be identified across the field. These samples were analysed at Silsoe between March and April 2001. A water release curve was created for the experimental site (Figure 3.4), to enable water-holding capacity to be recognised and aid in the analysis of soil moisture calculations. The available water content in the surface layer (0.1 m) between –10 kPa and –1500 kPa was 180 mm m^{-1}.

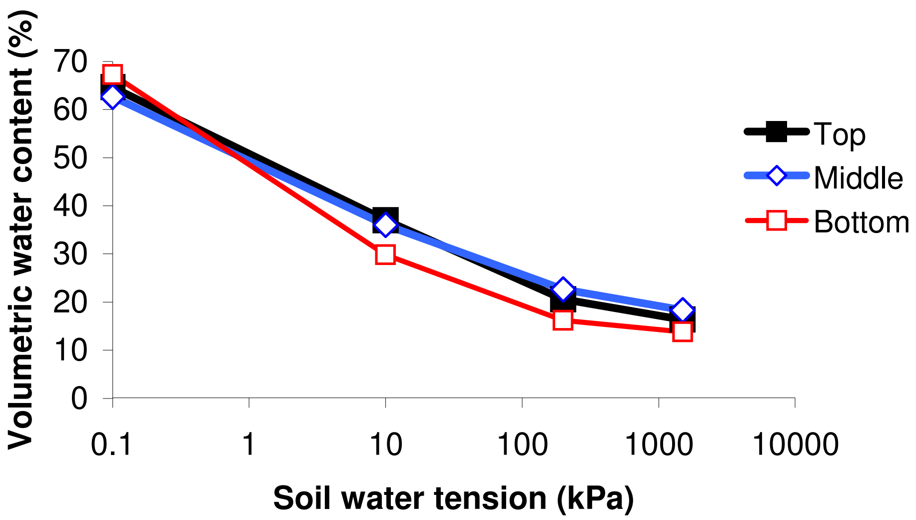


Figure 3.4. Water release curve for the experimental site at a depth of 0.10 m. Soil water tension for three positions within the research plots (top, middle and bottom) displaying similar volumetric water contents at water tensions.

3.3.2 Soil analysis

A full soil evaluation of the site was carried out in March 2004 after the irrigation experiments had finished. Six samples pits were dug within blocks 1 and 2 (Figure 3.4) allowing soils to be assessed at the top middle and bottom of the slope and at 10 and 35cm depths.

Particle Size Analysis (Pipette system)

There was a significant variation of clay at depth (35cm). This was not consistent between the left and right sides of the irrigation path or between the top and bottom of the slope. Sand and silt showed no significant position down or across the slope. The top soil was classified as Sandy Loam, whilst the sub soil was found to be Sandy Loan/Loamy Sand.

PH

There was a significant effect of depth and position (Table 3.1). However no effect across the slope or interaction was identified.

Table 3.1 pH measurements from six soil pits within blocks 1 and 2, at depths of 10cm and 35cm. ph levels range from 6.625 (top subsoil) to 6.975 (bottom subsoil). 6 samples were taken from blocks 1 & 2.

	Depth	
Slope position	Topsoil	Subsoil
Top	6.465	6.625
Middle	6.620	6.845
Bottom	6.600	6.975
s.e.d	0.0755 (significant at 1.4)	

Potassium and Phosphate

There was a significant effect of depth of potassium and phosphate (Table 3.2), no main effect of position down or across blocks 1 and 2 were identified.

Table 3.2 Potassium and Phosphate measurements (mg/kg) from six soil pits within Block 1 and 2, at depths of 10cm and 35cm. 6 samples were taken from blocks 1 & 2.

	Potassium (mg/kg)	Phosphate (mg/kg)
Topsoil	287	809
Subsoil	155	546
s.e.d	234	0.685

3.4 Experimental treatments and design

In February 2001, work began to establish the experimental site. The field had been sown with winter wheat therefore the area was lightly harrowed to remove the majority of the crop. Rabbit proof fencing was erected to protect the trees from grazing damage no additional tree protection, in the form of tree guards, was provided. The gates were positioned at the top of the slope to provide access to the site for machinery and irrigation equipment.

3.4.1 Tree species

Three tree species were selected, oak (*Quercus petraea*), ash (*Fraxinus excelsior*) and Douglas fir (*Pseudotsuga menziesii*) (Table 3.3). The selection criteria combined the need for good commercial species commonly planted in Britain with trees with high conservation value. All planting material was obtained from Bell Plantation Ltd, Towcester. All trees were pit planted, between 31 March and 10 April 2001, into the lightly harrowed. Trees were planted in a block design set out in figure 3.5. Blocks consisted of six plots, two plots of each species. 90 trees were planted per plot at 1.5 m intervals, 6 rows of 15 trees.

Table 3.3 Description of three tree species planted and two vegetation treatments.

Treatment type	Description of treatment
Tree species	Oak (*Quercus petraea*) Ash (*Fraxinus excelsior*) Douglas fir (*Pseudotsuga menziesii*)
Vegetation	Grass vegetation Herbicide-treated

3.4.2 Vegetation treatments

Two vegetation treatments were applied to all blocks (Table 3.3). For each tree species, in each block. One plot, for each species in each block, was vegetated and one had regular herbicide-treatment applied (Figure 3.5).

At the end of April 2001, the grass-vegetated treatments (eight plots of each species of tree) were seeded with a 'low maintenance set-aside' seed mixture comprising red fescue (*Festuca rubra*) and perennial ryegrass (*Lolium perenne*). The application of this seeding provided a suitable vegetation understory to give experimental differences to the tree plots.

The seed mixture was applied by hand broadcasting over the vegetation plots, and the surrounding land within the experimental area, at an application rate of 2.5 g of seed m^{-2}, in line with the seeding of agricultural set-aside areas. During 2001, the herbicide treatments received two applications of the glyphosate-based herbicide (PDQ) using a knapsack sprayer, across the whole plot, excluding trees, on 10 July and 12 September. This was applied across all the bare ground plots throughout the experimental period.

3.4.3 Initial experiment design April 2001-April 2002

The experiment design followed a line-source design similar to Burgess & Carr (1996), in the initial design this consisted of four 54 m x 22.5 m blocks (Figure 3.5). Each block was sub-divided into six 9 m x 22.5 m plots, which were planted with trees of different species. This allowed the use of a block analysis and enabled ease in data collection, during the running of experimental trials.

Species: the plots were planted with trees, in rows at 1.5 m intervals, each row being 1.5 m apart, so the plots consisted of 90 trees of the same species. The plots were randomly allocated to each of the three tree species, throughout the four blocks (Figure 3.5). This created eight plots of each tree species.

Vegetation treatment: within each block, the two species plots were allocated either as a vegetated or a bare-earth treatment (Figure 3.5).

Irrigation treatments: Five irrigation sub-plots of 9 m x 4.5 m were created within each of the plots (Figure 3.5). This provided 9 trees within each subplot, providing statistically relevant data sets for analysis. Although the stated distance for planting trees under woodland grant schemes is 2 m, the trees in this experiment were planted

1.5 m apart to maximise the number of trees within an irrigation treatment. On the basis of this design, a protocol was developed for analysing the trial data using an ANOVA analysis within Genstat software (Appendix A).

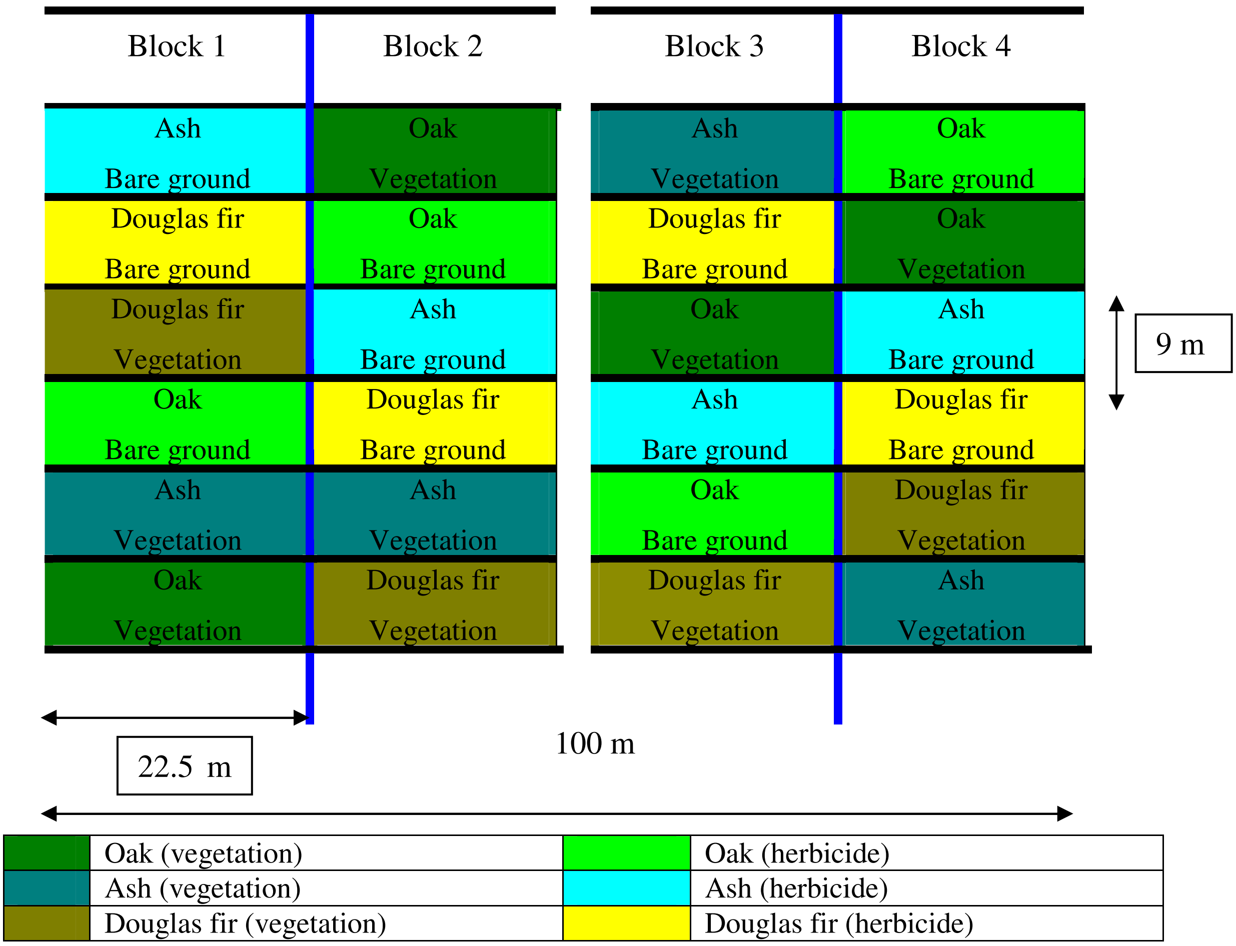


Figure 3.5. Original experimental layout showing the position of the three tree species and the position of vegetation and bare ground treatments.

3.4.4 Modified experimental design (April 2002-February 2003)

In the light of the results in 2001 and to negate the slope factors, a new experimental design was proposed for 2002. The four irrigation blocks, which originally ran in parallel from the top of the slope to the bottom (Figure 3.5) were changed to a group block design (Figure 3.6), consisting of four 27 m x 25 m blocks. With the changes to the experimental design, alterations to the statistical analysis were also made (Appendix A).

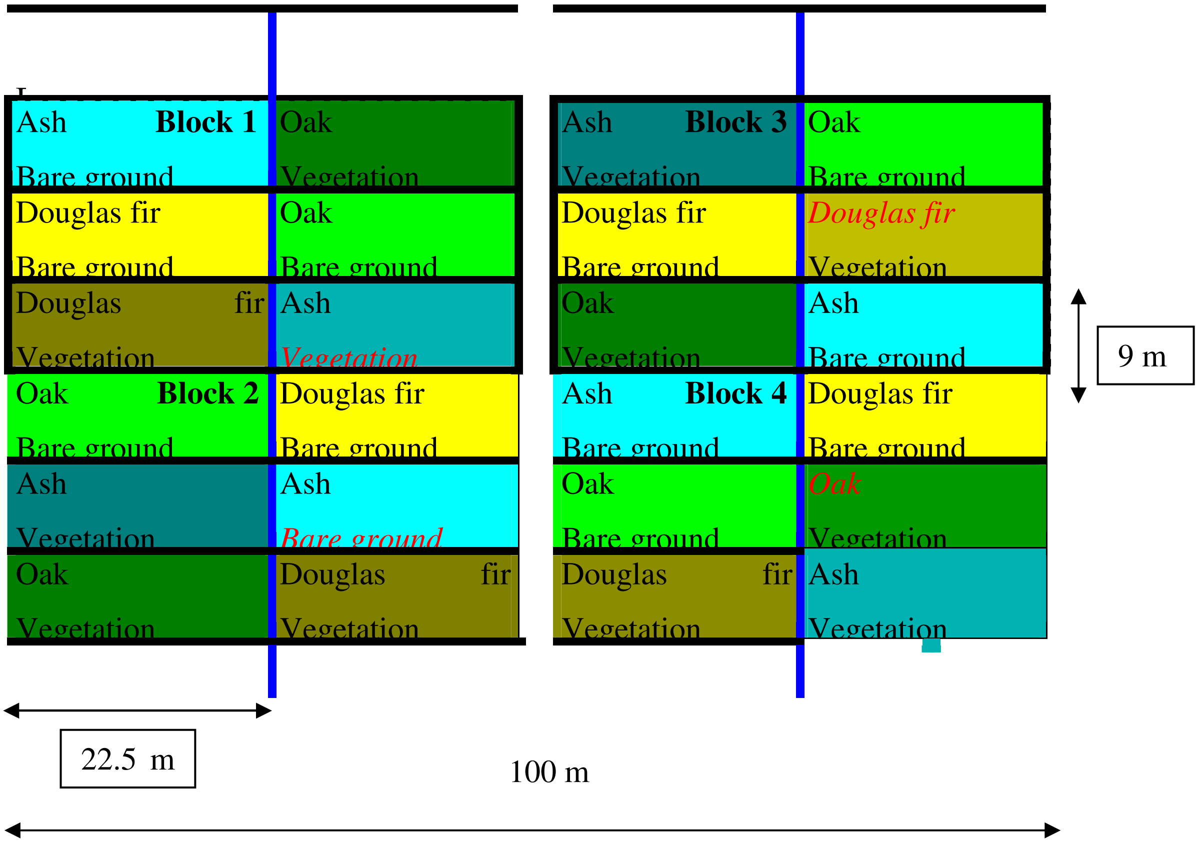


Figure 3.6 Modified experimental layout showing species and vegetation treatments (April 2002-February 2003). Showing changes in species position (species name highlighted) and treatment (treatment type highlighted).

Species

A modified planting design was implemented to allow the new blocking design to be established. This involved the movement of two plots of trees, vegetated oak, row B – block 3, was replaced with Douglas fir, row E – block 4, in the original experimental design. The trees were dug out of the plots and swapped with the corresponding tree in the other plot, reducing the time in transportation.

At the beginning of 2002, 200 Douglas fir and 270 oak were purchased as replacements for dead trees which occurred throughout the first year of growth. The minimal number of ash, which did not survive were replaced from existing stock. Planting took place during February 2002. Replacements were also planted early in 2003, with 87 Douglas fir and 279 oaks being replanted. The ash plots again had minimal losses and were replaced using existing individuals, not under any experimental treatments.

Bare-ground treatment

To finalise the changes in block design a herbicide and vegetation ash plot were changed, row C – block 1 had herbicide applications stopped and the vegetated row E - block 2 was given herbicide applications throughout the year. A number of herbicide treatments were applied throughout 2002, statistically removing vegetation from these plots. The first application on 2002 was applied on 27 March with a follow up application on the 18 April. Other applications were applied on the 24 May 14 June, 28 June, 16 July, 2 August and 24 September.

3.2 Statistical analysis

Statistical evaluation of data collected was calculated via Analysis of Variance (ANOVA) test using Genstat statistical software using a random block design (Table 3.4). The statistical design also changes to accommodate the reconfiguration of the experimental plots, these can be found in Appendix A. All statistical outputs, of the various data analyses, are presented in the results of the respective chapters.

Table 3.4. Statistical analysis of growth data using Genstat (April 2001-April 2002)

4 Blocks
5 irrigation treatments (I_0,I_1,I_2,I_3,I_4)
3 tree species (oak, ash, Douglas fir)
2 vegetation treatments (bare-ground (B), grass-vegetation (G))
120 plots of 18 trees at 1.5 m x 1.5 m spacing

4 IRRIGATION TREATMENTS AND SOIL WATER MEASUREMENTS 2001-2002

This chapter describes the imposition of irrigation treatments during the first two years of the experiment, and the effects on the soil water content in respective treatments.

4.1 Irrigation treatments

The experiment was designed to allow five irrigation treatments, which provided statistically valid variations in water application. Each of the five irrigation sub-plots received varying amounts of water ranging from full irrigation, closest to the irrigation path I_4, to no irrigation I_0 (rain only), at the extreme sides of the plots (Figure 4.1). The experimental design allowed a line source travelling sprinkler system to irrigate the tree plots along two continuous lines running between blocks 1 – 2 and blocks 3 – 4 (Figure 4.1).

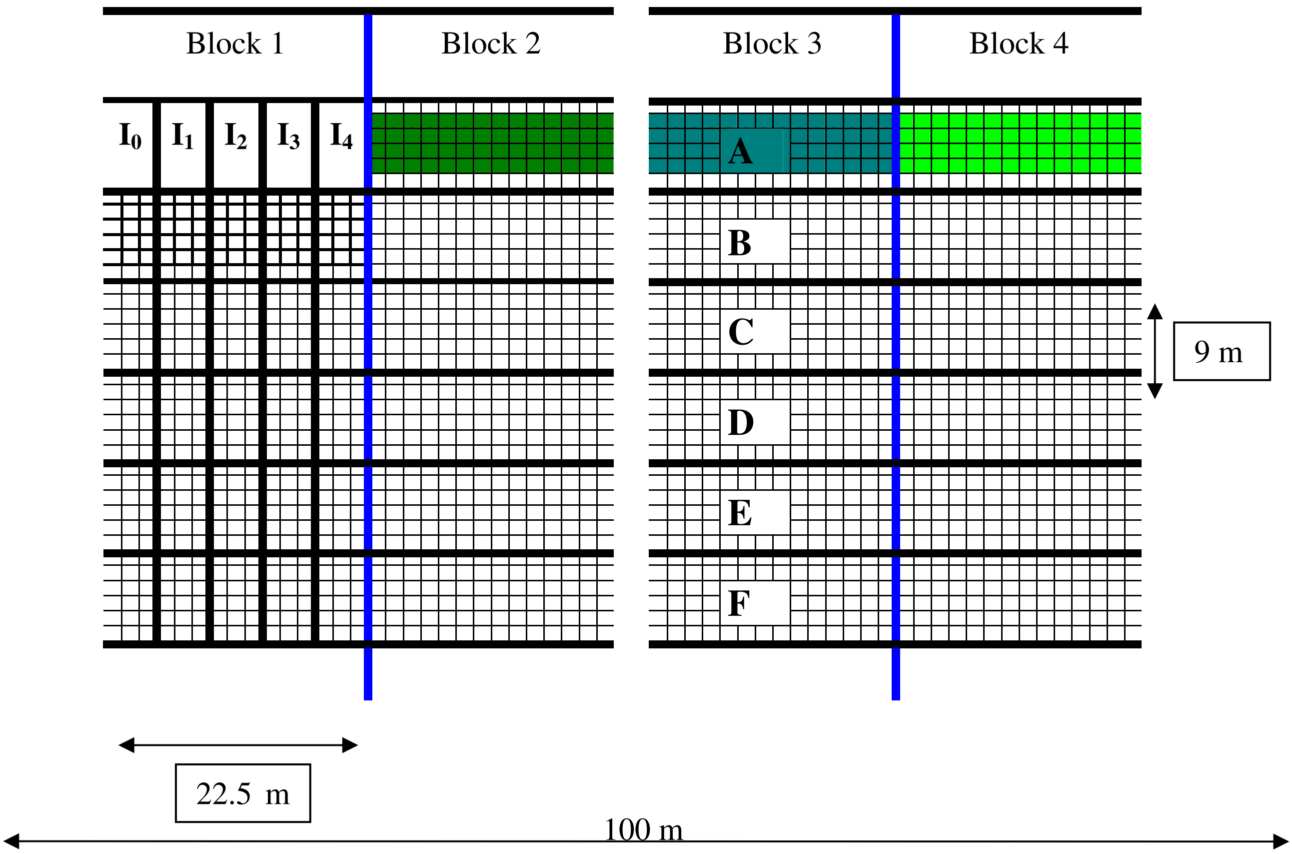


Figure 4.1. Experimental layout 2001, showing irrigation treatments, irrigation subplots and individual tree position (middle of each square). The blue lines indicate course of the irrigator.

4.2 Imposition of irrigation treatments

The experiment was irrigated using a Rain Train self-travelling sprinkler, which travelled along a 2 m path. During 2001 the system was powered by a small pump that ran from a tractor power-take-of, drawing water from a water tank, thus allowing the correct pressure to be generated to create the required water spread. During 2002, the irrigation system was powered by a petrol-driven pump attached to a storage water tank positioned at the top of the experimental area. Both systems provided adequate coverage of water, however the latter (later used in the 2003 experiments) allowed a greater efficiency in resource use.

A weekly application of water was envisaged, between May and September, to complement any precipitation over the three years. This was designed to vary considering the levels of rainfall and soil moisture each week. In reality application came down to the ability to run the irrigation system as often as possible. However this varied between years due to a number of constraints explained below.

4.2.1 Year 1

In 2001, irrigation was only applied on 16 July and 20 August due to time constraints and other commitments placed on the required machinery. Water application was calculated through the use of catch cans, positioned in the middle of each sub plot. No significant difference, in application depth (mm), was found within each irrigation subplot (I_0-I_4) and position within blocks 1, 2, 3 and 4. However there was a significant difference between irrigation subplots (p>0.05). The greatest water concentration occurred within subplots I_4, with 49.7% of the total application being deposited to these subplots. The percentage of water received by subplots I_0 was 0.2% in total, with subplots I_3, I_2, and I_1 receiving incrementally declining percentages (Figure 4.2).

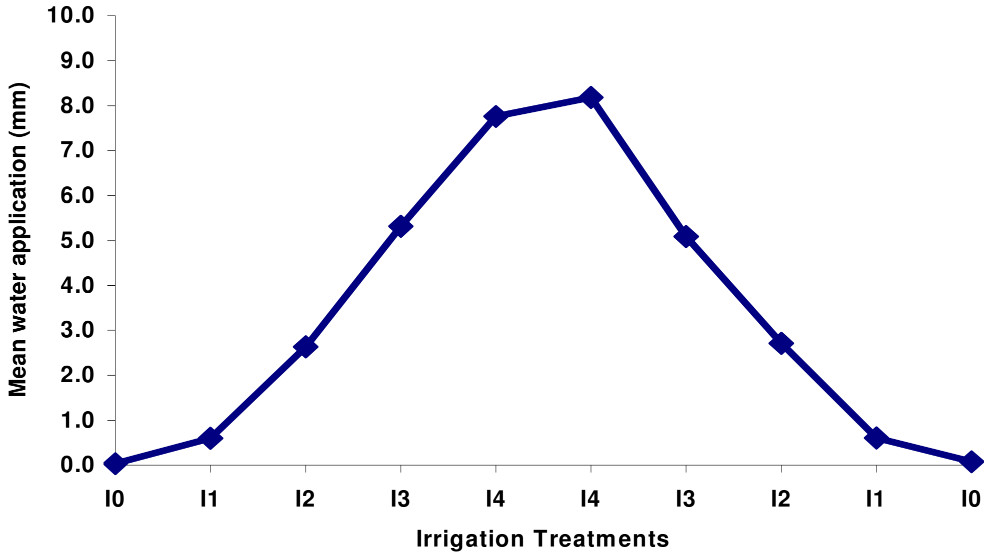


Figure 4.2 Total mean water applications of all irrigation plots for 2001 (Irrigation treatment mean; I_0=0.05, I_1=0.60, I_2=2.68, I_3=5.20, I_4=8.00). Two applications were applied during this season.

4.2.2 Year 2

In 2002, irrigation was only applied to blocks 1 and 2. Although the irrigation design data analysis has altered (Chapter 3), the application of water to the treatment plots remained the same. The application of irrigation took place on 7 June, 21 June, 30 June, 26 July and 14 August. Apart from the first application (7 June) a full irrigation run over blocks 1 and 2 occurred. The spread, created by the sprinkler system, produced good coverage of water over all plots and application to each irrigation subplots were at the desired levels (Figure 4.3).

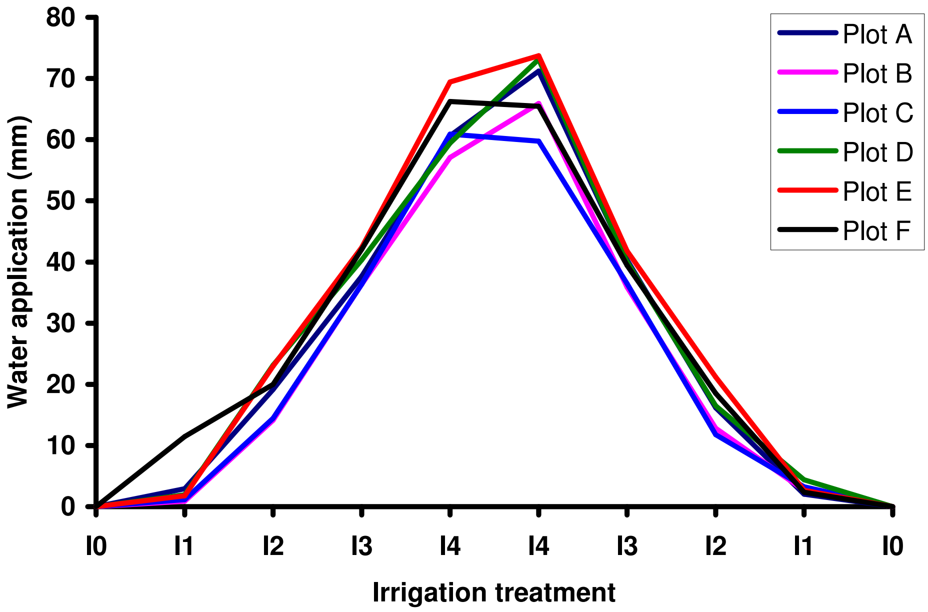


Figure 4.3 Irrigation applications for blocks 1 and 2 during 2002. Showing the even distribution of water applied to all plots (plots treatment mean; A=22 mm, B=23 mm, C=25 mm, D=26 mm, E=28 mm, F=27 mm).

During both years no significant difference (ANOVA evaluation between plots) was identified between the upper and lower plots in the irrigation trials (Figure 4.3). The use of powered pumps controlled the water pressure entering the sprinkler systems, effectively controlling any variation which may have been caused by the drop in height over the experimental site.

4.3 Methodology for neutron probes

4.3.1 Placement of neutron probe access tubes

Between June and July 2001, a total of 36 2 m long access tubes were installed in blocks 1 and 2, between tree rows three and four of each plot (Figure 4.1). Three subplots from each plot were chosen I_0, I_2 and I_4, which would give a representative sample of the irrigation applications across the plantations.

Description of equipment and health and safety precautions

A neutron soil moisture probe was used to record soil water levels at different depths. Measurements were made by dropping the probe into the aluminium tubes and recording data through the pulse counter (Neutron Probe Instructions and Safety Regulations, Cranfield university, Silsoe). Initial training was given, in site, by Cranfield University, Silsoe staff (Gabriela Lovelace) in the safe use and storage of the neutron probe.

Standardised count in water

In 2001 it was not possible to take a standardised reading in water as there was no facility available on site to allow a calculation of a water standard measurement Rs. Therefore the readings for 2001 are only presented as counts in the soil. In March 2002 a neutron probe calibration unit was positioned at the top of the experimental site, this consisted of a 200 litre plastic drum, with a probe tube inserted into the middle, approximately 100 mm above the top of the drum. This was placed in the ground, the top of the drum level with the soil surface and the drum was filled with water. Water counts were taken and soil water content was calculated using the standard calibration equation for a sand soil.

Collection of water content data

During the 2001 season, the readings were limited in number due to difficulties mentioned above. Readings were taken on 15 July 2001 for the four plots of ash. On 5 October 2001 readings were taken from each of the plots within blocks 1 and 2. The readings were recorded at depths of 30, 50, 70, 90, 110, 130, 150, 170 and 185 cm from a reading of 0 cm when the neutron probe was placed on the tube. In 2001, the height of the top of the access tube above the ground varied from 20 to 190 mm, with a mean of 107 mm. Assuming that the probe was initially 10 cm above the ground, the above readings equate to approximate soil depths of 20, 40, 60, 80, 120, 140, 150 and 175 cm. This provided consistent depth measurements across the experimental area allowing comparisons between site position and depth.

4.3.2 Neutron probe readings 2002

In the 2002 season neutron probe measurements were taken on 11 and 31 May, 14 and 28 June, 15 July, 1 August and 27 September. All the access tubes were cut to a height of 50 mm above the ground, thus readings were recorded at depth of 25, 45, 65, 85, 105, 125, 145, 165 cm.

4.4 Results

4.4.1 Effect of irrigation treatments on moisture reading: 2001

In the absence of a neutron probe calibration, the results from the 5 October 2001 were plotted as direct readings from the neutron probe. These readings showed that the surface layers were relatively wet, with a dry layer at a depth of about 40 cm, and that below this depth the soil became wetter (Figure 4.5). There was little statistical correlation between the irrigation treatments and moisture readings, due to the minimal number of water applications. The last irrigation application was six week prior to these probe readings.

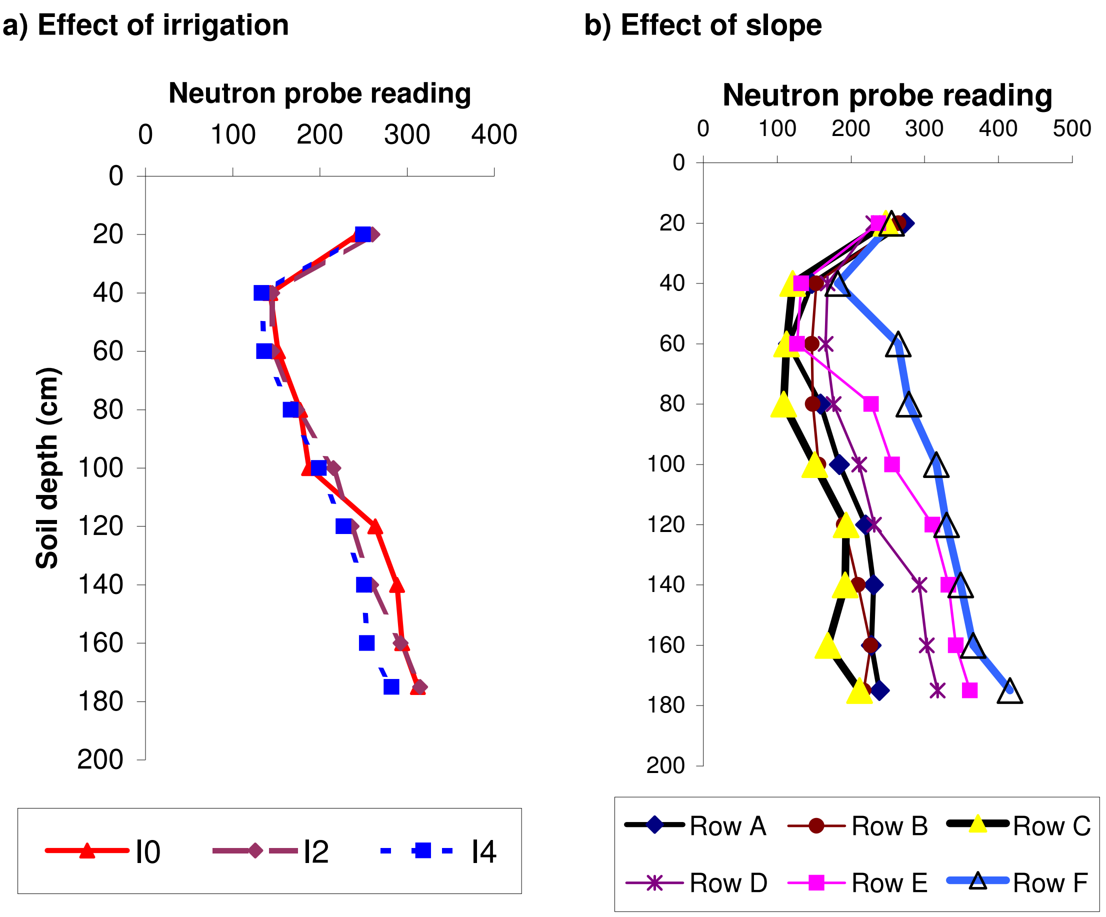


Figure 4.5 Mean neutron probe reading (counts) on 5 October 2001 for a) the three recorded irrigation treatments, and b) the six neutron probe row for blocks 1 and 2. Showing changes on soil moisture at depth and position.

4.4.2 Effect of row

If the neutron probe readings are viewed down the slope, using the plots design in 2001, then the wettest site was the bottom row (F). The driest areas were the top three rows (A, B, and C). The surface of all the plots were similar to a depth of top 40 cm, with an increasing moisture content at depth especially in rows D, E and F (Figure 4.5b). Recent precipitation would have given this initial uniformly high reading at a depth of 20 cm (Figure 4.5b). However the soil conditions would quickly dry, as seen in the soil moisture release curve for the experimental site (Figure 4.6), with the changing levels of soil moisture rising towards 180 cm.

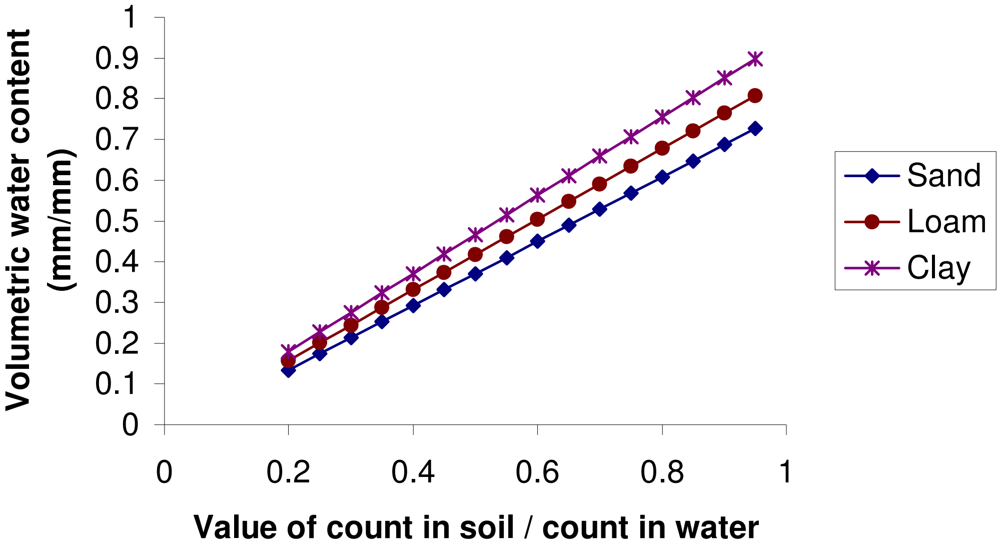


Figure 4.6 Example of standard relations between neutron probe reading and volumetric water content (Long & French, 1967).

The neutron probe readings taken in October 2001, showed that the wettest area was in the bottom northern-most corner of the plot (Table 4.1). However there was a significant increase in soil moisture down the slope from A to F.

Table 4.1 Mean neutron probe readings (counts), taken on the 5 October 2001, across blocks 1 and 2 highlighting the increased soil moisture in the lower plots.

	I0	I2	I4	I4	I2	I0
A	174	162	195	223	246	215
B	176	171	180	160	250	149
C	168	134	155	144	192	183
D	203	193	158	207	213	168
E	223	233	216	234	244	239
F	252	231	280	281	316	316

Key	
<150	
150-199	
200-249	
250-299	
>300	

4.5 Results 2002

4.5.1 Effect of new block design

In 2002, the neutron probe measurements highlighted the need for the new block arrangement (Chapter 3). Between May and September 2002, there was a general drying out of the soil profile (Table 4.2). Moisture levels decreased throughout the soil profile, although block 2 (rows D, E, and F) remained wetter the deeper the measurements were taken, with the least moisture difference found below 120 cm. Block 1 (rows A, B and C) showed approximately the same decline throughout the measurement depths (Figure 4.6).

Taking the mean neutron probe reading as an indicator of soil water status, the wettest area tended to be in the bottom right hand corner of block 2 (Table 4.2). This is reflective of the soil moisture found in 2001 (Table 4.1). The driest part of the experimental area was row B irrigation plot I_0. By September 2001 the differences in soil moisture throughout block 1 had disappeared although rows A and B, plot I_0, remained consistently dry (Figure 4.7). Again identifying the drying process shown in Figures 4.5.

Table 4.2 Mean moisture in a) May and b) September 2002, for blocks 1 and 2. Using amalgamated data measured from between 0.25 and 1.40 m depth.

a) Average soil moisture in May 2002

	I0	I2	I4	I4	I2	I0
A	0.28	0.25	0.27	0.32	0.32	0.25
B	0.23	0.25	0.26	0.25	0.37	0.37
C	0.26	0.27	0.25	0.24	0.27	0.35
D	0.28	0.27	0.25	0.28	0.29	0.27
E	0.29	0.33	0.34	0.31	0.31	0.33
F	0.31	0.35	0.38	0.40	0.41	0.37

Key	
< 0.19	red
0.20-0.24	yellow
0.25-0.29	green
0.30-0.34	cyan
0.35-0.39	blue
> 0.40	dark blue

b) Average soil moisture in September 2002

	I0	I2	I4	I4	I2	I0
A	0.18	0.22	0.22	0.27	0.23	0.25
B	0.17	0.22	0.22	0.24	0.25	0.28
C	0.21	0.20	0.22	0.21	0.17	0.18
D	0.18	0.20	0.24	0.24	0.23	0.23
E	0.23	0.20	0.19	0.26	0.10	0.22
F	0.18	0.20	0.22	0.23	0.25	0.28

Key	
< 0.19	red
0.20-0.24	yellow
0.25-0.29	green
0.30-0.34	cyan
0.35-0.39	blue
> 0.40	dark blue

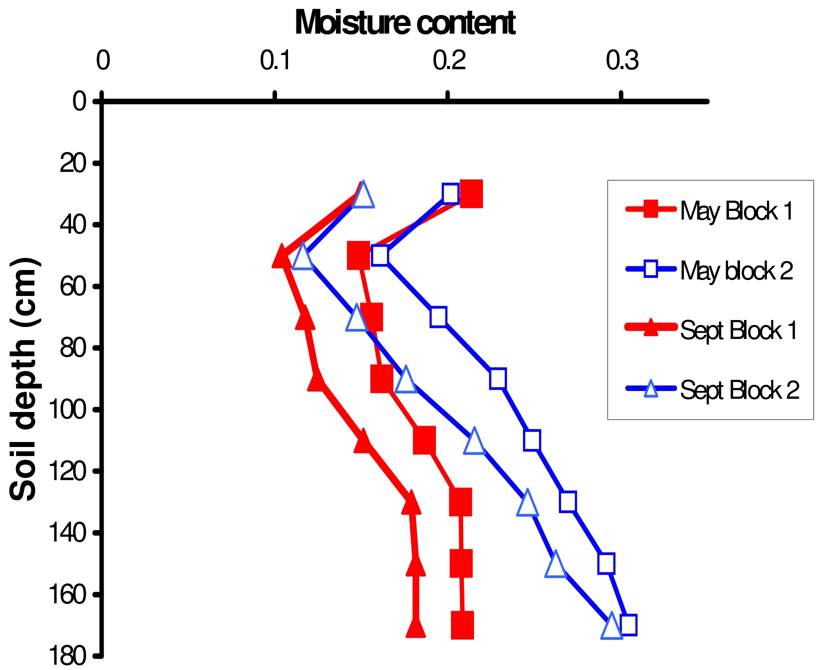


Figure 4.7 Comparison of soil moisture content in block 1 and block 2 between May and September 2002. Both blocks show reductions in soil moisture from May to September.

4.5.2 Effect of irrigation treatments

In 2002, there was no significant difference between the soil water content between the irrigation subplots (Figure 4.8). When the data was further analysed using just the measurements from the top 25 cm, there was again no significant difference in irrigation subplot position (Figure 4.9). change in soil moisture did occur between dates with a drying at all recorded depths (Figure 4.8) and dates (figure 4.9).

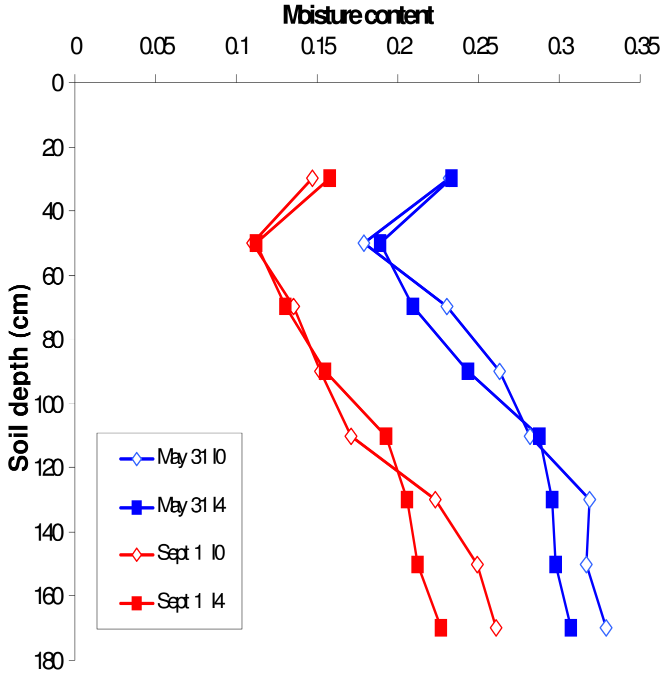


Figure 4.8. Effect of irrigation on soil moisture content in May and September 2002. Irrigation subplots I_0 and I_4, in blocks 1 and 2.

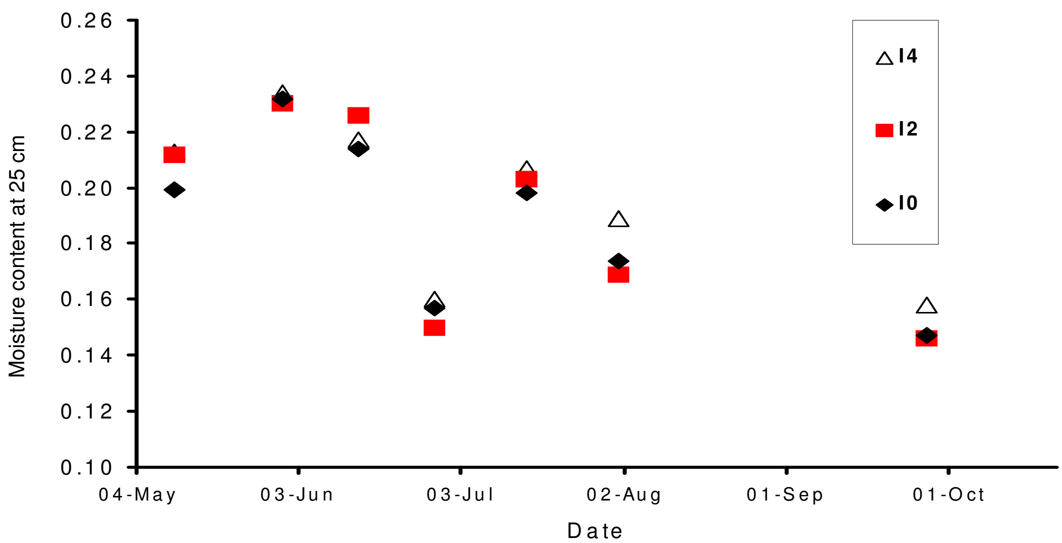


Figure 4.9. Mean moisture content in top 25 cm. Irrigation subplots I_0, I_2 and I_4, in blocks 1and 2, between may and October 2002.

4.5.3 Effect of vegetation treatment

When the vegetated and herbicide plots were analysed independently a statistical difference was established. ANOVA analysis of soil moisture in the top 250 mm of the vegetation treatment (0.1469) was less ($P<0.05$) than that in the herbicide treatment (0.2117). The differences only showed at the 250 mm levels within the herbicide and vegetation plots (Figure 4.10). There is a still a difference in soil moisture between June and August, and at different depths (Figure 4.10), however there was a different moisture profile of that of the soil moisture content of the block design (Figure 4.7).

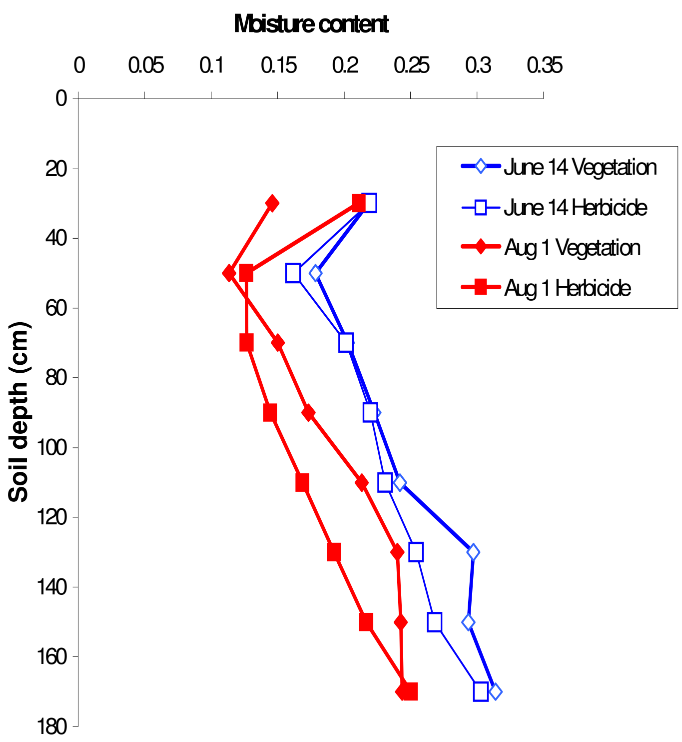


Figure 4.10. Effect of vegetation removal on soil moisture in June and August 2002 from blocks 1 and 2. Soil moisture in the herbicide plots decreased at depth more than the vegetation plots.

4.5.4 Predicted effect on soil water deficit (2002)

The soil water deficit (Figure 4.11) was created with the daily rainfall data from Pitsford and the evapotranspiration (ET) data from Silsoe (no ET data was available from Pitsford weather station at that time with Silsoe providing reliable data for this prelimary stage). The irrigation treatments applied to I_4 showed a marked increase in

SWD from June 2002. Irrigation was applied on five occasions between June and August. However there was still a decline in SWD throughout the year.

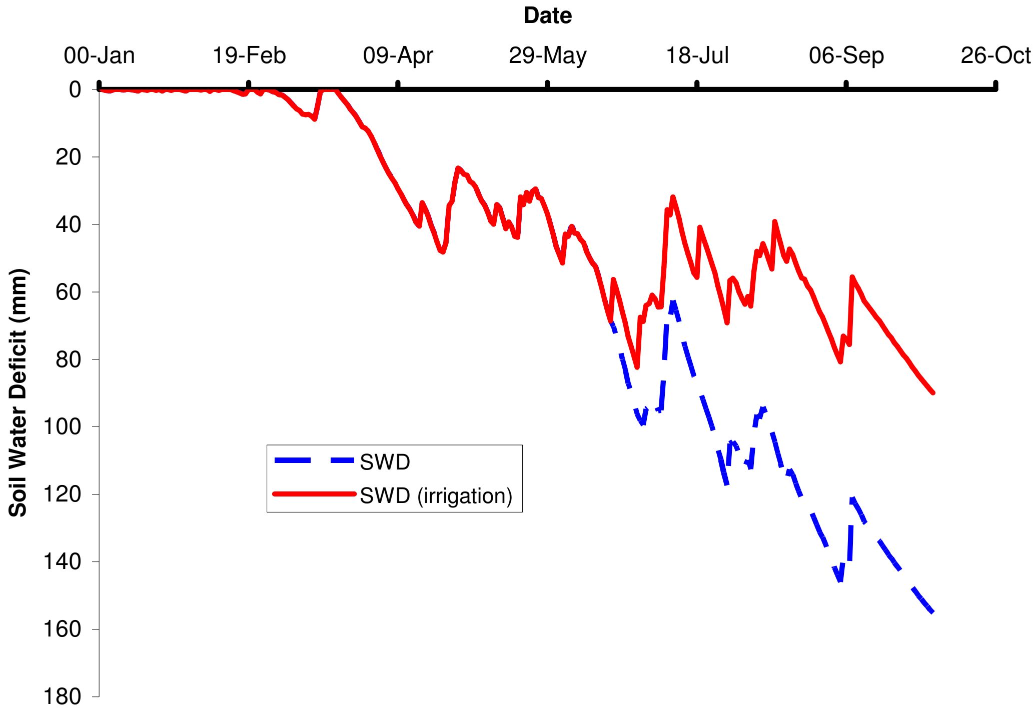


Figure 4.11. Predicted soil water deficit calculated for January to October 2002, using Pitsford rainfall and Silsoe ET data. (Pitsford ET data not available over this period). Showing a difference in SWD in irrigated and non- irrigated subplots.

4.6 Review of data

4.6.1 Initial measurements in 2001

In 2001, the lack of sustained irrigation treatment meant that there was no measurable change in soil moisture between the irrigation subplots. However the application spread (Table 4.2) showed a very good pattern of distribution, which set a precedent for future trials. The application rates were very low (figure 4.3) probably having minimal effect on tree growth or survival. Due to the limited irrigation applied during the year.

Significant differences in moisture levels were identified throughout the six rows. With much higher moisture readings in the lower rows D, E, and F (Figure 4.10), this became more apparent lower in the soil profile (below 60 cm). However this was almost certainly a factor of ground water not irrigation levels.

4.6.2 Measurements in 2002

Irrigation levels were addressed in 2002 by increasing the water levels applied to the tree plots. The irrigation data and predicted soil water deficit readings (Figure 4.11) indicated that there should have been a measurable difference in the soil moisture of the irrigation subplots. However this was not recorded in the neutron probe measurements (Figure 4.8 and Figure 4.9).

The potential storage capacity in the top 0.25 m of the soil (uppermost neutron probe reading) was calculated (from the highest and lowest water content), the amount of water required, to effect the first moisture reading of the neutron probe, would be 20 mm. The actual amount of water applied, through the irrigation process, showed only a maximum of 17.7 mm in the I_4 subplot, thus not significant to reach the level identified or affect the moisture calculations. The time intervals between the water application and neutron probe readings were also considered to be too long for any increase in SWD to be identified, highlighting any significant changes in surface soil moisture.

Herbicide applications on soil moisture

The soil moisture was mapped at a depth of 25 cm for the August probe readings, this highlighted a trend that the plots that had herbicide applications had a higher moisture level than the plots with vegetation cover (Figure 4.2). However no significantly different measurements were identified.

4.7 Conclusions

The soil moisture results from 2001 and 2002 identified the following points. The results of the irrigation treatments, during 2001 and 2002 had not provided any reliable data set to show distinct differences in soil moisture. Therefore it is unlikely that a high enough quantity of water was applied allowing infiltration into the soil profile, and affect the first probe depth measurement at 0.25 m. A significant difference in soil moisture between the vegetated and herbicide plots was found in the top level of the soil in 2002. However no conclusive results could be deduced for the experiment. A general trend in soil moisture was identified down the slope, if deep neutron probe measurements were taken into the equation, although this moisture content must be contributed to ground and not surface water supplies. The modification of the experimental design has allowed a more valid evaluation of plot treatments, negating the slope effect found in 2001.

5 TREE RESPONSES 2001-2002

This chapter describes the effect of species, herbicide treatment and soil-water status on tree survival and growth during 2001 and 2002. Growth and survival rates of the different tree species have been focused within blocks 1 and 2, which received a full range of irrigation treatments during these years. Due to time constraints and site maintenance requirements blocks 3 and 4 were removed from the field trials.

5.1 Methodology

The full layout of the experiment and the treatments imposed in 2001 and 2002 are described in Chapter 3. The irrigation treatments and resulting soil water deficits are described in Chapter 4.

5.1.1 Tree survival

The end of year measurements assessed survival rates for species as a whole and individuals. The criteria used were to assess each tree for signs of bud formation (and green leaves in the case of Douglas fir), scraping a small area of the bark for confirmation if required. However the latter was only performed to confirm death and not as a prerequisite for every tree. Many of the trees, which had died earlier in the season, had been previously identified before the November census.

5.1.2 Tree height and diameter

Measurements were recorded between the ground and the tallest limb to standardise the recordings (measurements recorded in mm). If an individual tree had more than one lead shoot the tallest was always recorded. Tree diameter was measured using a single measurement on each tree using digital callipers at ground level (measurements recorded in mm).

5.1.3 Statistical analysis

Statistical evaluation of tree growth data followed the design set out in Chapter 3. Only individuals that were deemed alive at the end of the growing season were used within the statistical analysis.

5.2 Results

5.2.1 Tree survival

In 2001, the Analysis of Variance showed a significant effect of species ($p < 0.001$), herbicide ($p < 0.05$) and a significant herbicide x species interaction ($p < 0.01$) in terms of survival (Table 5.1). The data were not transformed for this initial analysis.

Table 5.1 Mean survival rate (%) in 2001 of each of the three species and two herbicide treatments for all blocks.

	Vegetated	Herbicide	Mean
Oak	41.7	49.4	45.6
Ash	99.7	97.2	98.5
Douglas Fir	86.7	66.1	76.4
Mean	76.0	70.9	

Note: Standard errors of differences of means
between species, sed = 5.82% (df 30)
between herbicide treatments, sed =2.00% (df 15)
between herbicide and species treatments, sed =6.62% (df 15)

Effect of species

In 2001, there was a significant difference in survival rates between species (Table 5.1). Ash had an exceptional performance rate, with a total survival of 98.5%. The survival level of Douglas fir was 76.4%, after initially growing very slowly in many plots. Oak showed the highest mortality rates with only a 45.6% survival.

In 2002, tree survival increased from the previous year. Ash again displayed the highest survival of >99%, with only six losses, all of which have occurred through rabbit damage or vandalism. Douglas fir had a 88% survival, this was greater than the 2001 season. Oak showed an increase in survival compared to 2001, with a 61% suvival, although there were heavy losses in particular plots.

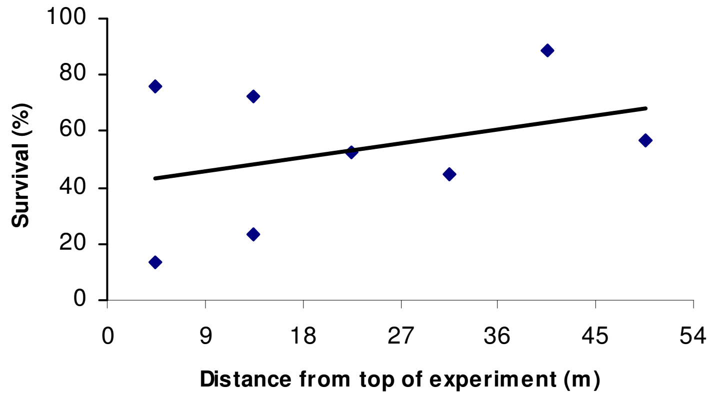
Vegetation treatment

Overall species survival under the vegetation treatment (76.0%) was greater than that in the herbicide treatment (70.9%) during 2001 (Table 5.1). However whereas the oak survived substantially better within the plots with herbicide applications, both the ash and Douglas fir showed an opposite survival performance, with the Douglas fir survival substantially increasing under the vegetation treatment (Table 5.1). Ash showed no significance for either treatment due to few individual deaths in this species.

Effect of position

Under the experimental design, established in 2001, the effect of slope could be evaluated. There was no significant effect of position down the slope on the survival of ash, again due to low death rate. Oak showed a significant effect (p<0.01) of survival and plot position. With high mortality in rows A and B, and an increased survival towards the bottom plots E and F. Douglas fir also showed a significant effect (p<0.01) of survival on plot position. The species displayed greater survival rates within the lower plots D, E and F (Appendix A.3).

a) Oak



b) Douglas fir

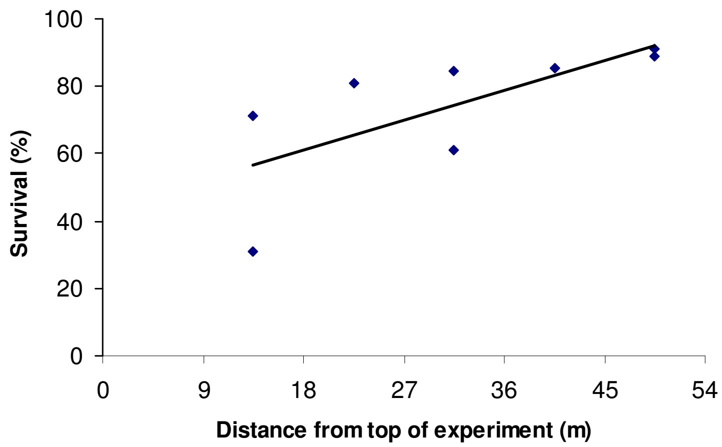


Figure 5.1 Effect of position on the survival rates in a) Oak and b) Douglas fir. The latter showed a significant correlation r_s=0.710 (p<0.05) were as oak showed no statistical relationship.

In 2002, there was an increase in herbicide applications (Chapter 3), which has provided a significant treatment effect over the experimental site. The combination of position and treatment had differing effects on survival of the tree species. Ash and Douglas fir have shown very little change as both had good survival rate, however the survival of oaks in herbicide plots varied little compared to the vegetated plots, which had greater survival in the lower plots (Figure 5.2).

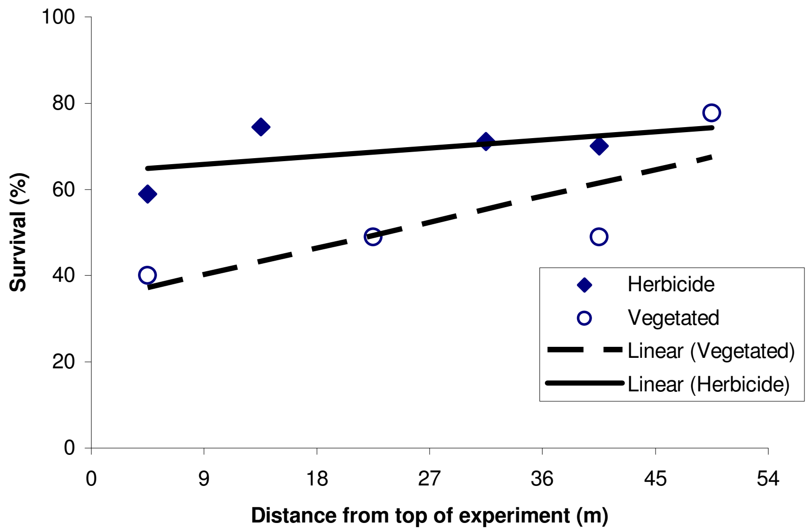


Figure 5.2 Effect of position in on the survival rate of oak under vegetated and herbicide treatments (2002).

The adjustments in block design, and the transplanting of trees and treatments, may have affected the survival and growth rate of trees affected. However in the Douglas fir plot that was transplanted with the oak (block 3 and block 4) the loss was only two individuals. Compared to the oak, which sustained 46 tree deaths, although this was not greatly different from the survival rate of other oak plots in the experiment. Therefore no significant deference was identified between transplanted trees and comparable plots of the same species.

5.2.2 Tree height

Effect of species

On 23 April 2001 at the start of the experiment, there was a significant difference between species height after planting (Table 5.2). The data collected for the 28 November 2001 census again showed a significant difference. In April 2001, oak was the tallest tree species with a mean height of 878 mm, but in November 2001, ash had the highest mean value at 974 mm (Table 5.2). Ash also showed the greatest increase in height (184 mm) out of the tree species. Douglas fir had a negative incremental growth with a mean reduction in height of 4 mm (Table 5.2).

Table 5.2. Effect of species on height (mm) for all individuals, in all blocks, in 2001.

	April 2001	November 2001	Calculated difference in height
Oak	878	919	44
Ash	788	974	184
Douglas Fir	440	445	-4
Standard error of difference	12.48	15.81	11.14

Vegetation treatments

In 2001, there was no significant effect of herbicide treatment on height growth throughout the three tree species (Table 5.3). Oak increased in height under both treatments throughout the two years. As did ash, although this species displayed a consistently higher mean height in the herbicide plots (Table 5.3). Douglas fir showed a decrease in height between April 2001 and November 2001, in the vegetated plots (Table 5.3).

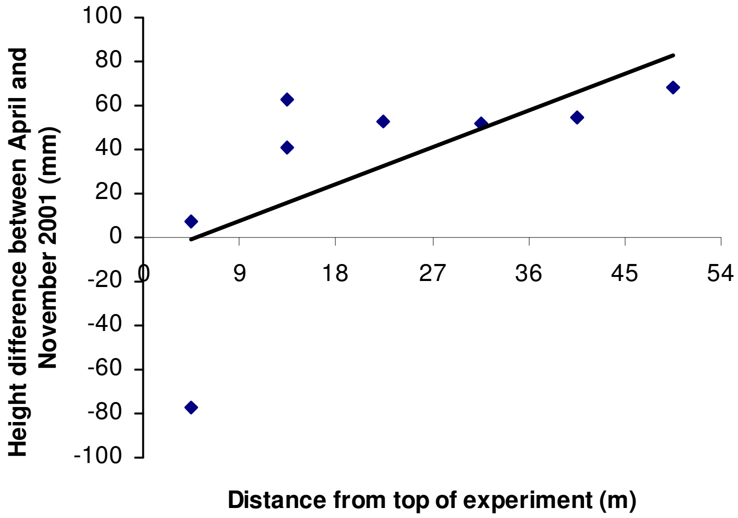
Table 5.3 Effect of herbicide and species on tree height (mm), for all blocks, between 2001 and 2002.

	Oak		Ash		Douglas fir		S.e.d
	Herbicide	Veg	Herbicide	Veg	Herbicide	Veg	
23 Apr 01	882	898	813	762	437	418	21.0
28 Nov 01	936	913	1002	947	438	405	22.8
24 Mar 02	985	936	1000	951	445	454	18.1
20 Dec 02	1087	1039	1192	1067	546	558	30.3

Plot position

Ash showed a significant difference in height growth and plot position over 2001 (p<0.05) but no effect of plot position. There was a significant effect (p<0.01) on height growth in oak and differences in plot position. There was a significant effect (p < 0.001) on height growth in Douglas fir with plot position (Appendix A.4). Analysis of the data showed that tree height increased down the slope from row A to row F. However no direct relationship could be identified to the effect of position within the experimental blocks (Figure 5.3).

a) oak (2001).



b) Douglas fir (2001).

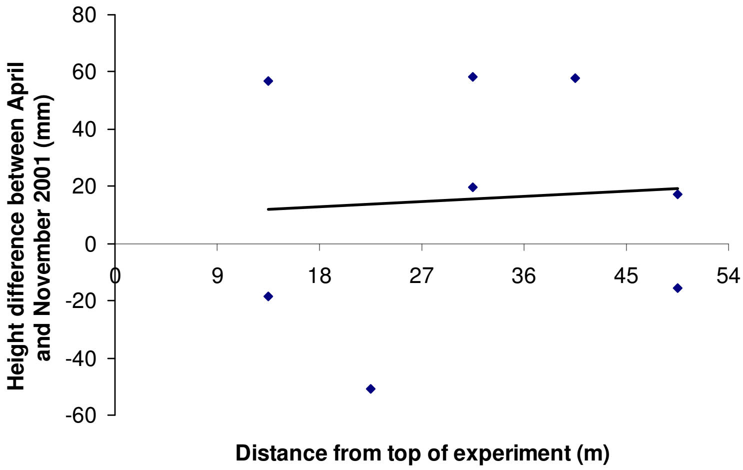


Figure 5.3 Effect of position on height difference in a) oak and b) Douglas fir for all blocks.

Height measurements were collated on four occasions after the baseline data was collected on the 23 April 2001. Replanting and measurements were undertaken in March 2002 and growth measurements were recorded in November 2002 (Table 5.4).

The oak trees showed similar growth rates between vegetated and herbicide plots (Table 5.4). The Douglas fir trees also showed similar growth rates in the vegetated and herbicide plots (Table 5.4).

Table 5.4. Effect of herbicide on species and incremental tree height (mm) from all blocks.

	Oak		Ash		Douglas fir		S.e.d
	Herbicide	Veg	Herbicide	Veg	Herbicide	Veg	
Apr-Nov 01	53	30	185	183	-11	-14	13.4
Nov-Mar 02	0	-1	-1	5	0	1	2.5
Mar-Dec 02	63	55	191	114	97	103	22.1

Ash showed greater tree heights gains in the herbicide plots. However, there was a significant height advantage in the initial planting (Table 5.4). Where there was more consistent herbicide spraying in 2002 the incremental growth rates in the herbicide plots can were greater (Table 5.4).

5.2.3 Tree diameter

Effect of species

On 23 April 2001 at the start of the experiment, there were differences in stem diameters at the base of the tree for each species, with oak displaying the widest at a mean of 13.9 mm (Table 5.5). In November 2001, oak still had the greatest diameter with a mean of 14.3 mm. The largest mean increase of the 2001 growing season was Douglas fir at 0.95 mm, with ash increasing their diameter size by 0.62 mm (Table 5.5).

Table 5.5 Effect of species on diameter (mm) 2001, showing differences in species diameter between April and November 2001 and mean difference between census dates.

	April 2001	November 2001	Difference
Oak	13.9	14.3	0.23
Ash	13.4	14.1	0.62
Douglas fir	7.5	8.3	0.95
S.e.d	0.21	0.26	0.30

Oak displayed a steady development in diameter, apart from the replanting stage in March 2002. Ash showed a greater increase in diameter in the herbicide than the vegetated treatment in 2002 (Table 5.6).

During the winter 2001/2002, due to the high number of replacements, the mean diameter for oak in both vegetated and herbicide plots decreased (Table 5.6). Although a substantial number of Douglas fir were also replaced, some growth throughout the winter period may have improved the growth rates of this species between November 2001 and March 2002 (Table 5.6). Ash showed a steady expansion in diameter between years. Incremental growth increased during the 2002 season with the vegetated and herbicide plots showing a similar increase (Table 5.6).

Table 5.6 Effect of herbicide and species on diameter (mm), fro all blocks, between 2001 and 2002.

	Oak		Ash		Douglas fir		S.e.d
	Herbicide	Veg	Herbicide	Veg	Herbicide	Veg	
23 Apr 01	14.0	14.0	13.2	13.6	6.9	7.6	0.31
28 Nov 01	14.6	14.5	13.9	14.2	8.6	7.6	0.41
24 Mar 02	13.9	13.5	13.9	14.2	8.9	8.2	0.37
20 Dec 02	15.7	14.8	19.0	16.0	12.5	11.4	0.62

Vegetation treatment and plot position

In 2001, there was no significant effect of herbicide treatment on diameter growth rates throughout all three tree species. No effect of distribution, diameter increase and plot position was found.

Table 5.7 Effect of herbicide and species on tree diameter increment (mm) for the tree species and plot treatments between 2001 and 2002.

	Oak		Ash		Douglas fir		S.e.d
	Herbicide	Veg	Herbicide	Veg	Herbicide	Veg	
Apr-Nov 01	0.21	0.61	0.72	0.66	0.57	0.41	0.31
Nov-Mar 02	-0.16	-0.01	0.00	0.00	0.00	-0.02	0.07
Mar-Dec 02	2.03	1.31	5.07	1.78	3.40	3.17	0.52

5.3 Review of data

The tree species used in this experiment showed a substantial difference in terms of species survival, incremental height and diameter growth rates. The data collected for each of the subplots in 2001 were assessed as a whole, as little irrigation was applied. These results are discussed in terms of survival, diameter, height and plot position.

5.3.1 Survival in 2001

During the initial year, there was great variability in survival between the three tree species. Ash had the greatest survival rate with only 1.5% mortality. The dead trees resulted from stem damage, either through rabbit grazing (rabbit problem early in the experiment) or through vehicle damage, which occurred in December 2001. None of the ash appeared to have died through direct environmental factors.

Although the ANOVA analysis shows a significant effect of plot position and survival, the individuals which were replaced, were located in specific plots. For example in block 3 row D, thus producing a significant factor. Certainly the position of the ash plots in relation to the slope does not seem to have been a factor in its survival.

Oak suffered the highest mortality rate of the three species, with only a mean survival of 45.6% (Table 5.1). Oak showed a surprisingly good initial establishment in April/May (personal observation). However, with the prolonged dry periods throughout the summer and erratic irrigation, mortality increased. The majority of losses can be found in rows A and B at the top of the slope. This would suggest a direct link with the soil moisture, as the neutron probe readings showed poor moisture retention, certainly with the initial planting depth (Figure 5.3). Survival rates of the oak tended to increase with the position down the slope.

Douglas fir showed similar results to that of the oak with a high mortality, although this was not confined to the position of the plot or soil moisture. Although the majority of the trees suffered some damage during the initial establishment phase, many of them showed substantial die back, and initial observations suggested higher mortality rates might have been expected. However, new growth started to show towards the end of the field season. These individuals were left, thus explaining the negative height measurements obtained for this species.

5.3.2 Survival in 2002

In 2002, a key factor was the consistent application of herbicide to the bare ground plots. This created a significant difference in the treatments. In 2002, survival improved compared to the death rate recorded in 2001. Ash still lost only six trees throughout the plots, not due to a specific environmental factor but principally through rabbit damage. These trees were replaced.

Douglas fir showed a significant increase in survival. Most of the losses came in the herbicide plots, but were not specific to any plot or position in the experimental site. Oak survival rates increased since 2001, however there was significant loss in a number of plots. The majority of the losses were in the top vegetated plots, and survival rates increased towards the bottom of the slope. The death rate does not seem to be reflected in the herbicide plots where survival has been consistent over the experimental area for all species.

5.3.3 Tree height

The trees which survived the first year's growing season showed a marked difference in height between the species. Ash displayed the greatest growth rate throughout all plots. The calculated difference in height was significantly more than the oak and Douglas fir.

Although oak suffered the highest mortality rate, the height development was significant. within the individuals that survived showing some growth throughout all the plots.

Although Douglas fir recorded poor rates of growth, many trees, after initial die back, produced new growth from the basal area (measured in the November 2001 recordings) these became the lead stems. Although height was not statistically significant, in this species, general growth on many individuals was good with much of the growth put into the lower limbs, consolidating health and stability.

5.3.4 Tree diameter

Tree diameter measurements displayed incremental growth increases throughout all of the tree species monitored. Oak showed the smallest incremental growth, and Douglas fir the largest. This would support the previous statement that Douglas fir utilised energy into establishment and not necessary directly into increased height development. Ash developed substantially in diameter.

5.3.5 Vegetation treatments

In 2001, the survival rates in the vegetation treatments depended on tree species. Ash displayed no real significant difference in survival between vegetation treatments or herbicide treatments. Ash mortality was very low throughout the experiment, with competition with ground vegetation being negligible. Oak showed a significant increase in survival within the bare ground plots. The reduction in water competition by the removal of herbaceous species may have aided survival for this tree species. This may suggest that oak is sensitive to water stress as suggested be Moffat (1999). Douglas fir showed greatest survival rates (20%) within the vegetated plots. Early observations in the fieldwork identified that Douglas fir within the vegetation plots established more quickly than the herbicide treatments. Many of these plots (especially rows E and F) initially had high wheat regrowth after the ground preparation stage, and poor grass mix establishment. The re-emergence of wheat controlling more competitive species may have aided this tree species survival, however no direct measurements were taken to highlight this factor.

The results showed no significant effect of vegetation treatments on tree growth during 2001. All species seem not to be adversely affected by either soil moisture or plant competition under the experimental regimes applied.

In 2002, ash underwent a significant incremental growth rate in both vegetated and herbicide treatments, however the increase in the herbicide plots was 77 mm more than that in the vegetated plots. This was reflected in the incremental diameter growth for 2002, with substantial statistical difference in size between treatments. The differences between the height and diameter sizes have highlighted the treatment effects of the herbicide applications.

All three tree species have performed better under the herbicide treatments, in at least one if not both growth measurements, showing a strong relationship with competition. To what extent that competition is for water or another resource cannot be identified. Although in Chapter 4 the irrigation treatments and soil moisture did not display a significant difference between vegetation and herbicide treatments, the identification of differing moisture levels in the top 250 mm may have impacted on the performance of all tree species.

5.3.6 Plot position

In 2001, there was a significant effect of plot position on tree survival of the oak and Douglas fir. By contrast, plot position did not have a significant effect on the survival of ash. Analysis of data showed generally better survival rates of oak and Douglas fir on the lower plots irrespective of vegetation treatment. This would suggest some link with soil moisture, in the initial establishment phase, however this has not been shown through any correlation of survival or growth difference against neutron probe data. This may be due to the minimal measurements, of both tree performance and moisture readings over the 2001 field season.

Plot position for the oak and Douglas fir also showed a significant effect on height development. Plot position did not have a significant effect on the height increment of the ash. Oak trees further down the slope put on more growth than individuals surviving in the top plots (Figure 5.3). Douglas fir also showed a significant difference in the analysis of variance, however no direct link to position can be established.

5.4 Conclusions

The survival and growth of ash, oak and Douglas fir during the 2001 season varied substantially. With the absence of irrigation it has given an opportunity to see how plot position within the experimental site has highlighted differences between these species. Although direct relationships could not be made between soil moisture and growth.

Ash showed no effects of stress or signs of mortality, in any plot position suggesting that at this early establishment stage it is unaffected to changes in soil water deficit. This underpins Moffat’s (1999) data, who identified SWD on yield class in larger specimens. Oak and Douglas fir both showed distinct signs of water stress, which significantly affected survival and growth. Many of the effects were exacerbated due to the lack of irrigation, this was clearly seen by the mortality rates encountered within the upper plots. This would have been negated to a large extent by irrigation, with only subplots I_0 and possibly I_1 displaying the results, which were found over the whole experiment. Early root penetration, especially by the smaller Douglas fir may have drastically affected performance due to the limited water application.

The data that was collated on tree performance over the two years, has given a good baseline of results in terms of tree survival and growth. However little can be concluded in terms of relationship between treatments. With the implementation of herbicide treatments in 2002, significant changes in growth were identified. In 2001 and 2002, the ‘effects of soil moisture' were primarily caused by the effect of slope rather than any limited irrigation treatment. The following conclusions can be made:

- There is a significant difference in survival between species and within species position and treatment.
- Tree growth, height and diameter, varies between vegetation and herbicide treatments.
- A structured irrigation approach would greatly enhance the likelihood of species’ variation to soil moisture.
- A consistent approach to vegetation control would provide distinct treatment and species responses.

6 IRRIGATION TREATMENTS AND SOIL WATER MEASUREMENTS 2003

This chapter describes the irrigation and vegetation treatments applied in 2003. Water applications were restricted to blocks 1 and 2, due to time and resource availability. A more structured approach to water application and soil moisture measurements were taken to clearly identify changes and influences on tree species (Chapter 7) and ground vegetation communities (Chapter 8).

6.1 Method

6.1.1 Application of irrigation

In 2003, irrigation was applied only to blocks 1 and 2. The irrigation was applied over a 16 week period between 28 May to the 10 September 2003. A total of 26 applications were made over this period, with 10 weeks having double runs (Wednesdays and Thursdays consecutively). The application of water took place on 28 May, 4 June, 11 June, 18-19 June, 25-26 June, 2-3 July, 9-10 July, 16-17 July, 24 July, 30-31 July, 6-7 August, 13-14 August, 20-21 August, 27 August, 3-4 September and 10 September. The spread, created by the sprinkler system, produced the required coverage of water over all plots and irrigation subplots (Figure 6.1). The collection and recording of water applied followed the previous two years methodology.

Due to the development in height of the trees in the experimental plots used, the sprinkler head was extended (1 m in height vertically) to remove interference by tree foliage to the irrigation runs. The use of this device from 25 June had no significant effect ($P>0.05$) on the application or spread of water applied.

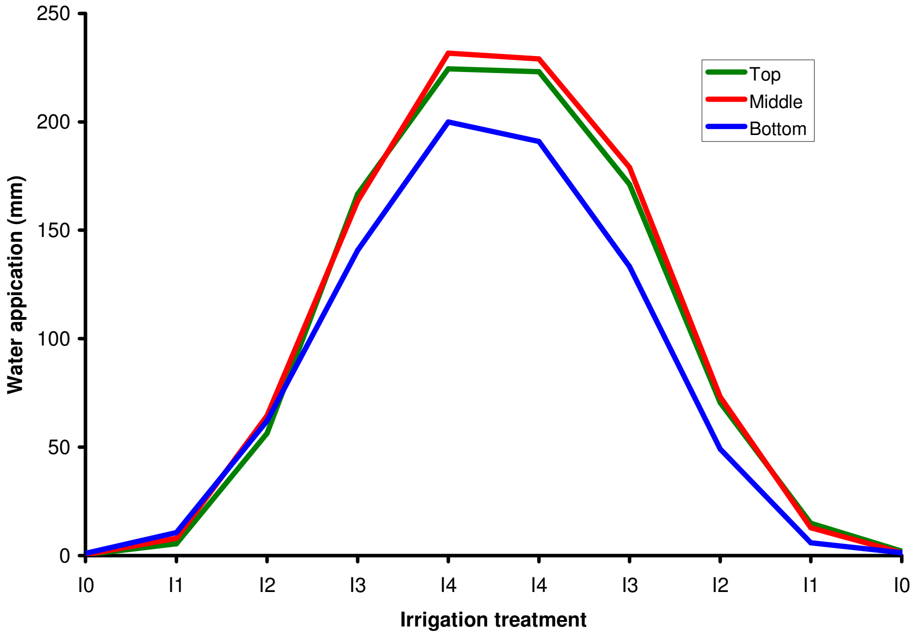


Figure 6.1 Irrigation of blocks 1 and 2 during 2003, showing mean spread of water application over subplots and between the top, middle and bottom areas of blocks 1 and 2.

6.1.2 Herbicide applications

In 2003, bare ground treatments were maintained through the application of herbicide (glyphosate) approximately every three weeks. The first applications in 2003 were applied in early April and continued throughout the irrigation period. This provided a clear distinction between vegetated and bare ground treatments with very little colonisation of ruderal species throughout the bare ground plots.

6.1.3 Neutron probe readings 2003

During the same period neutron probe measurements were taken (following a standardised methodology outline in section 4.3) on 31 May, 22 and 29 June, 5, 11 and 18 July, 14 August and 15 September. Readings were recorded at depths of 25, 45, 65, 85, 105, 125, 145, 165 cm as for the previous year. All recordings were taken within three days of irrigation being applied. This was to remove the difficulties in continuity of water treatments and soil moisture recording identified from the 2002 data.

6.2 Results

6.2.1 Predicted effect on soil water deficit

In 2003, the potential soil water deficit (Figure 6.2) was estimated with daily rainfall and evapotranspiration (ET) data from Pitsford weather station. April and May 2003 were particularly dry months, unfortunately irrigation was not applied during these months due to commitments of staff and student support. Following the imposition of irrigation treatments from the end of May, the irrigation, applied to I_4 and I_3, resulted in a marked decrease in the predicted soil water deficit (Figure 6.2). These calculations showed that the I_4 irrigation treatment was maintained at field capacity through most of July and August. The treatments I_0 and I_1, which received little or no irrigation, show no difference to natural soil water deficits (Figure 6.2).

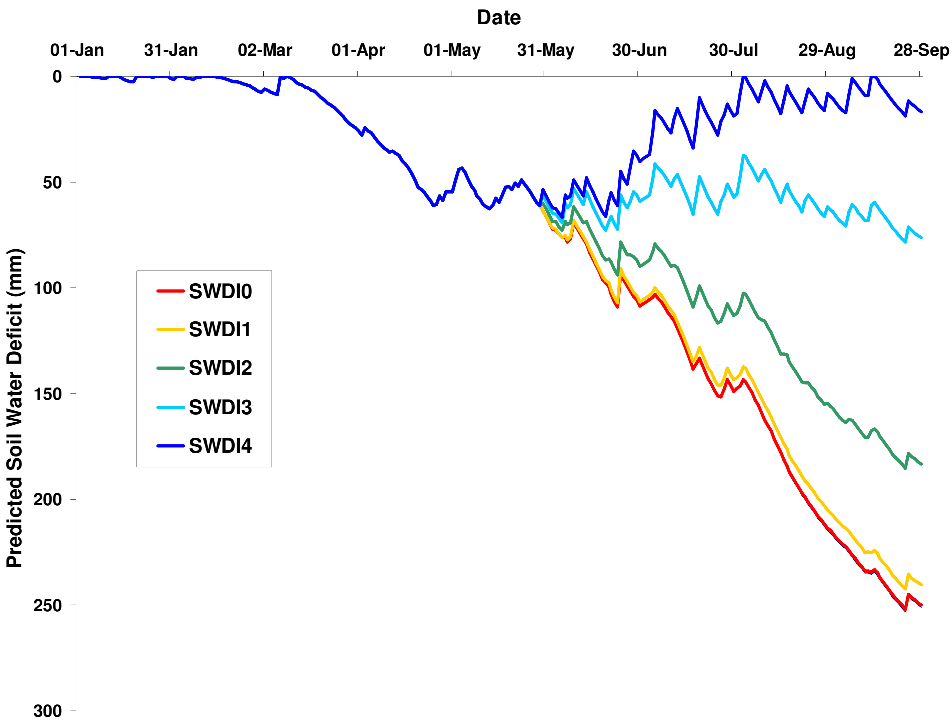
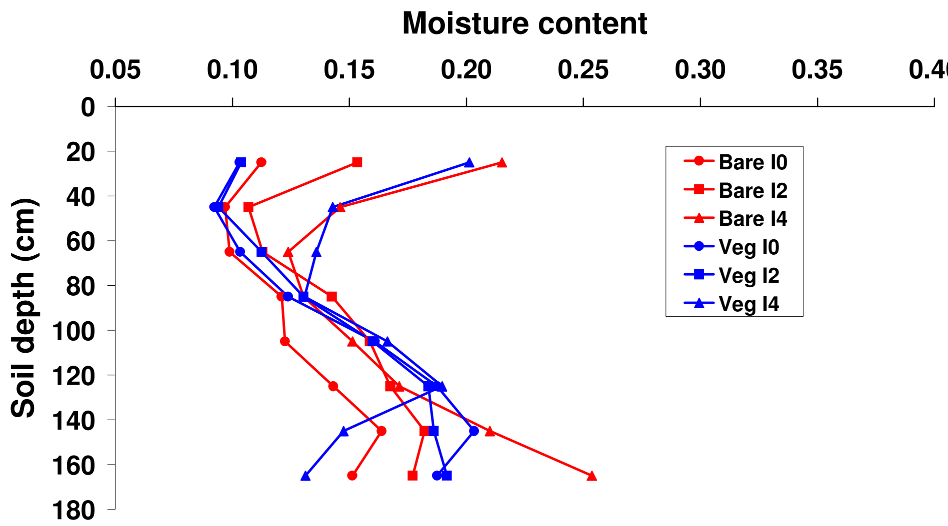


Figure 6.2. Estimation of potential soil water deficit during 2003, based on irrigation applications, rainfall and ET data from Pitsford School Northamptonshire.

6.2.2 Effect of slope

The changes in block design carried out before the 2002 sampling were continued for the 2003 survey period. Both blocks 1 and 2 have had similar water application through the irrigation treatment (Figure 6.1). At a depth of 25 cm, the soil moisture contents were similar (Figures 6.3). However below this depth in block 2 the moisture content was more varied. The vegetated readings showed greater water content which is due to the lower plots of the block being under the vegetated treatment. Certainly the I_0 plot readings were heavily influenced by the bottom plot that had been the wettest part of the experimental area.

a) Block 1



b) Block 2

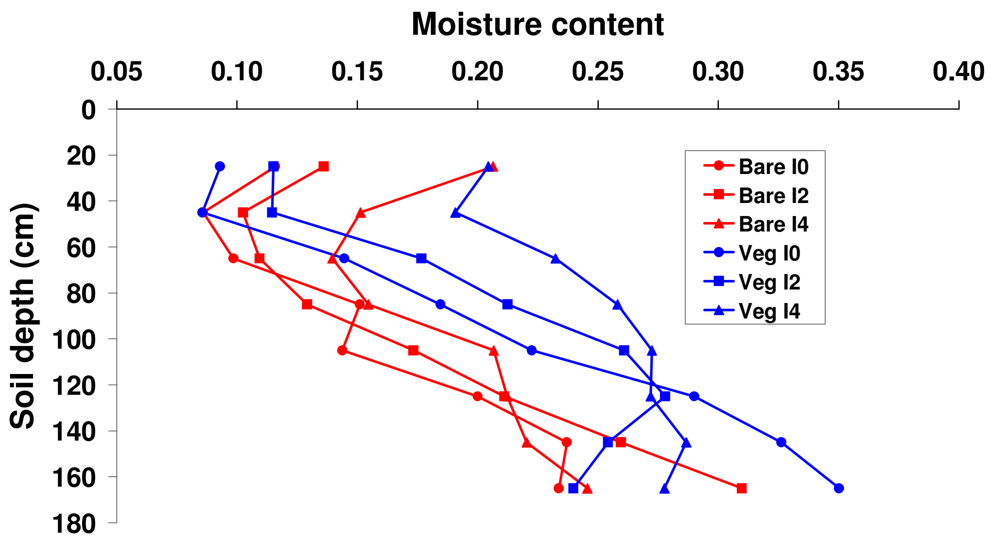


Figure 6.3. Mean soil moisture differences between irrigation and vegetation treatments for a) block 1 and b) block 2, for 2003.

6.2.3 Effect of irrigation

The irrigation applications between May and September 2003 resulted in a marked difference in soil moisture readings across blocks 1 and 2. Soil moisture readings taken in subplots I_4, I_2 and I_0 reflect the water applications to each of the areas (Figure 6.4).

Differences between the vegetation treatments also varied. Both the high irrigation (I_4), bare herbicide plots and the vegetation plots were similar in moisture content throughout the monitoring period (Figure 6.4). I_2 and I_0 displayed different moisture contents between the vegetation treatment favouring the bare ground plots in soil moisture.

The high moisture readings of the vegetated plots below 120 cm (Figure 6.4) are due to the dominance of these treatments towards the bottom of block 2. This was the lower part of the slope and has naturally better soil moisture at depth. However at this stage in tree development this should not have been a significant effect on the growth rates.

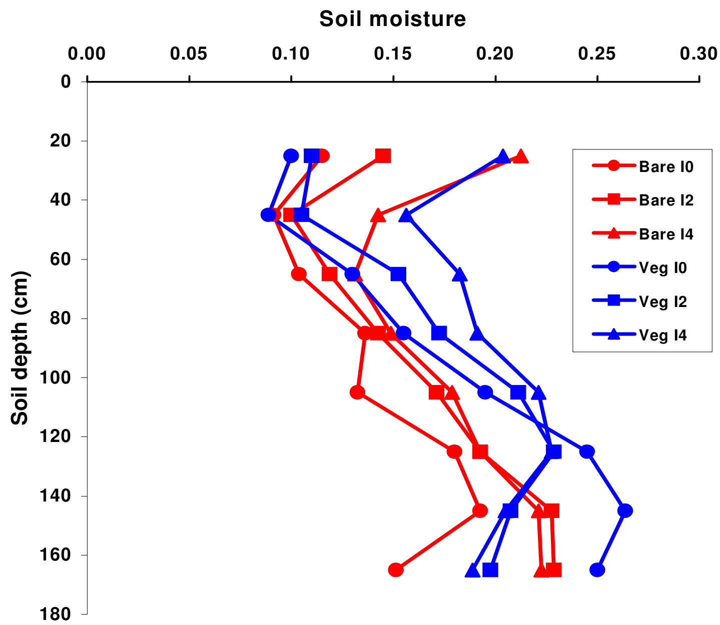


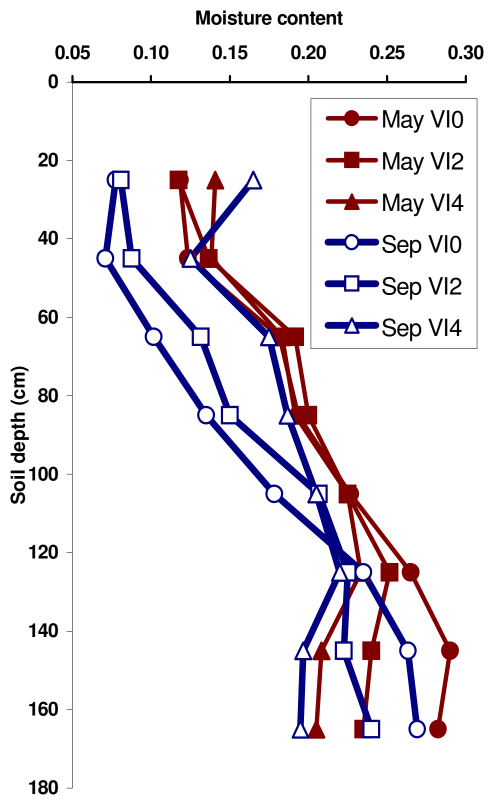
Figure 6.4. Combined mean soil moisture differences (blocks 1 & 2) between irrigation treatments (bare ground & vegetation) during 2003.

The bare plots were consistently drier that the vegetation plots irrespective of slope (Figure 6.3) or irrigation (Figure 6.4). The lack of transpiration within the bare plots allowed increased soil moisture in the top layers of the soil. The lower probe readings showed a much wetter profile (Figure 6.3b), which has been effected by ground water resources, however this would not have effected the tree or ground vegetation growth. The combined data (figure 6.4) shows a reduced impact of this over the experimental area as a whole.

6.2.4 Effect of vegetation

The neutron probe measurements recorded under the two vegetation treatments showed a difference in mean moisture content (Figure 6.5). Changes in moisture content between the beginning of the irrigation period and the end have been highlighted in Figure 6.5. There were significant reductions in soil moisture between May and September for both vegetated and bare ground plots.

a) Vegetated plots



b) Bare plots

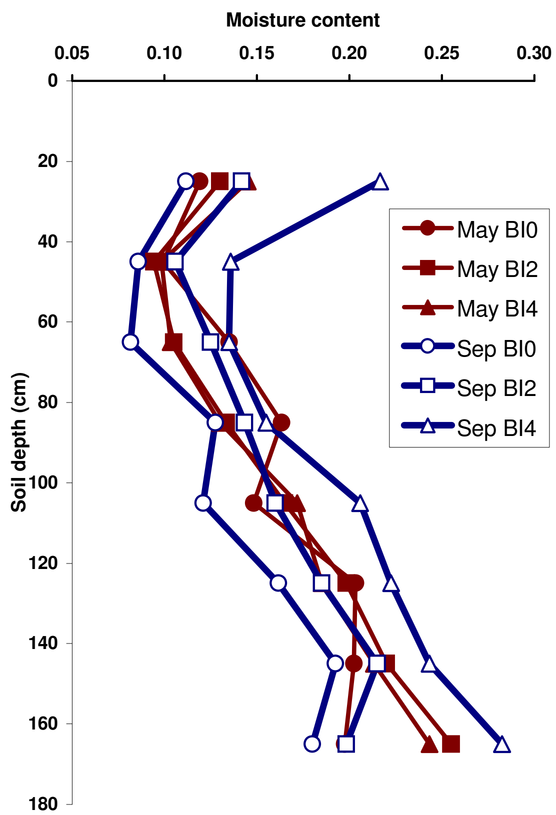


Figure 6.5 Effect of a) vegetated and b) bare soil on the change in soil moisture between May and September 2003 in blocks 1 & 2.

The surface layers of the vegetation treatments showed the greatest change over the irrigation period. I_4 plots increased in moisture content (Figure 6.5) whereas I_2 and I_0 plots decreased in moisture content. This would have been expected in the I_0 plots due to the limited application of water. The I_2 plots (Figure 6.5 (a)) suggested the level of irrigation was utilised by the vegetation.

The bare ground irrigation plots with similar moisture contents in May displayed differences in September (Figure 6.5 (b)). The I_4 plots substantially increased in soil moisture, with I_2 increasing slightly. I_0 plots decrease in moisture content, due to the distinct lack of water applied to these plots, but not to the degree displayed by the vegetated plots. Both treatments show limited influence of water application at depth, where the significance of water application had been negated by ground moisture content.

6.3 Discussion

6.3.1 Irrigation treatments

In 2003, the neutron probe recordings were closely linked to the water application, with readings taken within three days of the weekly irrigation applications. This allowed closer monitoring of irrigation treatments which was a error highlighted in the 2002 data. The increased level of water application between May and September 2003 unsurprisingly had a significant effect on soil moisture. The estimated potential soil water deficits (Figure 6.2) predict distinct differences between the irrigation treatments. This is supported by the neutron probe readings, which highlighted the effect of irrigation on the surface soil layers. However the further down the soil profile, the influence of irrigation was reduced (Figure 6.5). During the irrigation process the available soil water content is critical for irrigation timing (Girona, 2002). In this experiment these influences were not measured.

6.3.2 *Effect of slope*

In 2003, the application of water through the irrigation system negated the effects of slope identified in previous years. Within the top 50 cm of blocks 1 and 2 the moisture content was dictated by the irrigation treatments with higher moisture contents biased towards I_4 in both vegetated and bare ground plots (Figure 6.5).

Below the depth of 60 cm irrigation, was less effective in removing the difference between blocks 1 and 2. Block 2 had higher water content at depth, with the lower plots in this block influencing the overall moisture content substantially (Figure 6.5). Block 1 displays more clustered moisture content between irrigation plots below 60 cm (Figure 6.5). This is reflective of the dry soil in the upper half of the experiment.

Table 6.4 Mean moisture content (mm) in top 50 cm of soil in irrigation plots I_0, I_2 & I_4 for blocks 1 & 2 in 2003. Taken from neutron probe analysis.

	I0	I2	I4	I4	I2	I0
A	142	139	216	228	220	156
B	144	165	243	213	260	201
C	133	123	152	158	136	175
D	179	179	216	222	210	151
E	186	198	234	299	238	178
F	205	192	287	266	251	279

Key (mm)
<150
150-199
200-249
250-299
>300

Herbicide application on soil moisture

The vegetation plots were allowed to develop with no management since 2001 (Chapter 8). The herbicide applications on the bare ground plots (especially during the 2003 experiments), made a clear delineation between treatments. This has been identified in the data, clearly showing the differing moisture contents, between bare ground and vegetated plots and the irrigation treatments applied (Figure 6.5). Certainly in the upper soil profile water availability for tree utilisation has been reduced primarily by the competition with ground vegetation species. The lower recorded levels have been dominated by ground water, although of limited use for trees or herbaceous communities due to the depth, this has skewed the soil moisture data in favour of the vegetation plots if soil moisture data is taken as a whole.

6.4 Conclusions

The implementation of a sustained irrigation programme significantly highlighted differences in soil moisture throughout blocks 1 and 2. This clearly delineated between field capacity levels (I_4) and natural decreases in soil moisture (I_0).

By the application of high water volume and the timely recording of soil moisture, via neutron probe measurement, water availability can now be precisely related to tree and ground vegetation growth.

The effects of vegetation control, which again has been vigorously applied during the 2003 experimental session, has shown a variation in soil moisture and the possible uptake of water by herbaceous communities. Thus highlighting restrictions in water availability for the establishment and development of tree plantations.

7 TREE RESPONSES 2003

This chapter describes the effect of species, herbicide treatment and soil-water status on tree survival and growth during 2003. The focus, as for Chapter 6, will be on trees within blocks 1 and 2, which received a full range of irrigation treatments. The aim of this chapter is to identify relationships between water availability and growth potential of individuals and species. The range of water applications will be discussed and their influences on the survival, incremental height and diameter development over the year.

Trees within blocks 3 and 4 are discussed in terms of survival and the effects on species and herbicide application, however this is clearly stated when discussed.

7.1 Methodology

The full layout of the experiment and the treatments are described in Chapter 3. The irrigation treatments applied during 2003 and the resulting soil water contents are described in Chapter 6.

7.1.1 Tree survival

The end of year measurements (November 2003) assessed survival rates for all the trees. The criteria used followed the same, procedure as previous years, where all trees were assessed for survival through signs of bud formation (and green leaves in the case of Douglas fir), and by ascertaining the general fitness of individual trees.

7.1.2 Tree height and diameter

Measurements were recorded between the ground and the tallest limb (measurements recorded in mm). If an individual tree had more than one main shoot the tallest was always recorded. Tree diameter was measured using a single measurement on each tree using digital callipers at ground level (measurements recorded in mm).

Where trees within the experiment had died during 2002, replacement trees were planted and height and diameter measurements taken on 20 March 2003. Subsequently the height and the diameter at ground level of each tree was measured by the end of March 2003. At the end of November 2003, the height and diameter of each tree was measured again, together with details on survival. The effects of species, herbicide and irrigation on survival, tree height and tree diameter in March and November 2003 were determined using an Analysis of Variance with the Genstat 5.0 software package (VSN International Ltd). The effects on height and diameter increments over the year were determined.

7.2 Results

7.2.1 Tree survival in 2003

In November 2003, in blocks 1 and 2, there were significant effects of species (p < 0.001) and herbicide (p < 0.01) on tree survival. There was also a species x herbicide interaction (p < 0.05). There was no significant effect of irrigation on tree survival, although this ranged from 78% in the unirrigated I_0 plots to 87% in the fully irrigated I_4 plots.

The survival rate of the ash was 100% in all treatments and there was no response to herbicide (Figure 7.1). Although the survival of the oak was 94% and 78% in the vegetated and herbicide treatment respectively, this difference was not significant. However the reduction in survival by the Douglas fir from 81% in the vegetated treatments to 45% in the herbicide treatment was significant (p < 0.001) (Figure 7.1).

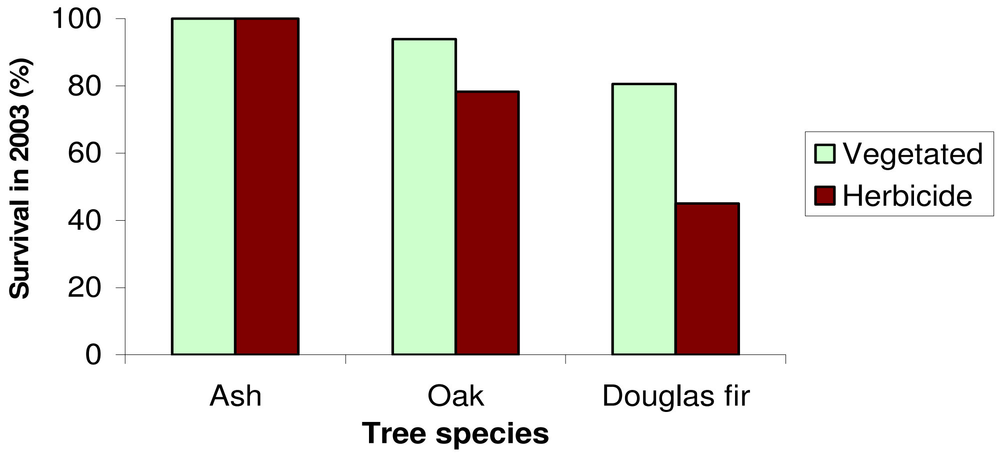


Figure 7.1. Effect of herbicide on the survival of three tree species ash, oak and Douglas fir (s.e.d = 9.06%; d.f. = 29).

The difference in the survival rates of Douglas fir between the vegetation treatments was primarily caused by very poor survival rate of 13% in the herbicide plot of Block 1 (Table 7.1). The mean survival rate in the other herbicide plots was 74-78% (Table 7.1).

Table 7.1. Survival of all trees under ground treatments, within blocks during 2003. Highlighting the location of tree plots and tree survival, within individual irrigation subplots (0-18). The shaded red areas highlight subplots where less than 25% survival occurred (Douglas fir).

	Vegetated	Herbicide
Block 1	60/90 (67%)	12/90 (13%)
Block 2	85/90 (94%)	69/90 (77%)
Block 3	70/90 (78%)	70/90 (78%)
Block 4	84/90 (93%)	67/90 (74%)

New block 1											New block 3									
18	18	18	18	18	17	16	18	16	16		18	18	18	18	18	12	9	10	14	9
1	0	4	4	3	18	17	13	13	16		10	13	15	17	15	14	15	15	16	10
8	7	13	16	16	18	18	18	18	18		16	14	14	11	10	17	18	18	16	16
New block 2											New block 4									
11	15	11	12	15	12	15	16	15	11		18	18	18	17	18	17	14	13	14	11
18	18	18	18	18	18	18	18	18	18		15	12	16	13	15	14	16	18	16	17
16	17	17	18	18	17	17	17	17	17		17	15	17	17	18	18	18	18	18	18

7.2.2 Cumulative tree survival

The number of surviving trees, over the three year period, that were originally planted in the experimental plots during March and April 2001, varied significantly between species ($p < 0.001$) and vegetation treatments ($p < 0.05$). No interaction or effect of irrigation was found. Ash, as consistently shown throughout the study, displayed a high original survival rate (mean = 17.6), irrespective of vegetation treatment (Table 7.2). Douglas fir showed above 50% survival of original planted trees (mean = 9.4), whilst oak showed only 26% overall survival (mean = 4.7).

Table 7.2. Percentage survival rates of trees species, under vegetated and herbicide treatments, from original planting in March 2001 to November 2003. Individual survival rates for irrigation subplots for blocks 1,2,3, and 4.

	Vegetated			Herbicide		
	Ash	Douglas fir	Oak	Ash	Douglas fir	Oak
Block 1	97%	52%	9%	94%	10%	14%
Block 2	100%	57%	53%	100%	81%	28%
Block 3	97%	57%	20%	97%	29%	38%
Block 4	89%	43%	39%	99%	91%	62%

New block 1											New block 3									
16	18	17	18	16	3	2	1	1	1		16	18	18	17	18	9	6	5	11	4
1	0	2	4	2	2	6	2	0	3		4	5	5	6	6	9	14	11	12	5
8	7	10	12	10	17	18	18	16	18		6	1	6	3	2	17	17	17	16	16
New block 2											New block 4									
4	3	3	9	6	11	12	15	5	8		18	15	16	15	16	10	10	6	12	1
18	18	18	18	18	18	18	18	18	18		13	9	12	12	10	10	7	7	4	7
8	11	12	7	10	13	15	16	15	14		14	12	11	15	13	17	18	18	18	18

7.2.3 Tree height

Effects of species and herbicide

In March 2003 prior to the anticipated summer growth phase, there were significant ($P<0.01$) effects of species and herbicide on tree height (Figure 7.2) but no interaction (Table 7.3). The mean height of the ash across vegetation treatments (1157 mm) was 17% greater than that for oak (989 mm), which was 76% greater than that for Douglas fir (563 mm). The mean tree height in the herbicide area was 12% greater than that in the vegetation treatment (954 mm) (Table 7.3). There was no significant effect of irrigation ($P=0.08$) and no significant interactions.

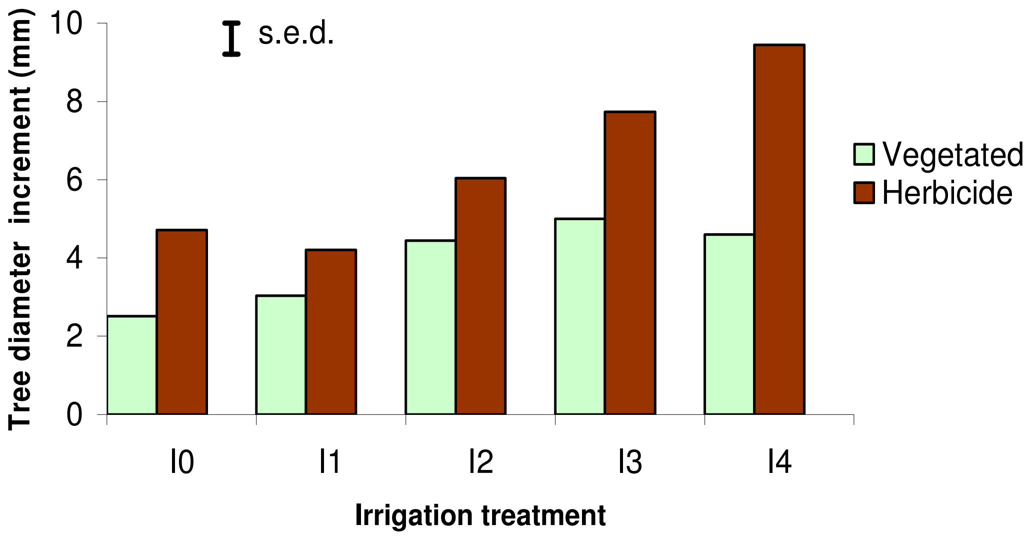


Figure 7.2. Tree height increment and irrigation treatments between vegetated and herbicide plots (s.e.d = 50.5 mm; df = 5).

Table 7.3 Effect of vegetation treatment on the height (mm) of three tree species in March and November 2003, and the height increment over the year.

	March 2003			November 2003			Increment		
	Veg	Herbicide	Mean	Veg	Herbicide	Mean	Veg	Herbicide	Mean
Oak	1046	932	989	1028	1174	1101	87	93	90
Ash	1222	1092	1157	1289	1529	1409	197	306	252
D Fir	533	593	563	794	946	870	224	236	231
Mean	852	954		1037	1217		169	212	
S.e.d species mean (d.f.10)			45			76			48
S.e.d vegetation means (d.f. 5)			19			26			21

Eight months later in November 2003, the effect of species ($P<0.001$) and herbicide ($P<0.001$) on tree height had become more significant. The mean height of the ash (1409 mm) was 28% greater than that of oak (1101 mm), which in turn was 27 % greater than the height of the Douglas fir (870 mm) (Table 7.3). The tree height in the herbicide treatment (1217 mm) was 17% greater than that in the vegetation plots. There were no significant interactions (Table 7.3).

The height increment over 2003 showed significant species ($P<0.05$) and herbicide ($P<0.01$) effects on tree height. The mean incremental height of the ash (252 mm) was 8% greater than that of the Douglas fir (231 mm), which in turn was 61% greater than the incremental height of the oak (90 mm) (Table 7.3). The incremental tree height in the herbicide treatment (212 mm) was 20% greater than that in the vegetated plots (169 mm). There were no significant interactions.

Effect of irrigation

There was a significant ($P<0.05$) effect of irrigation treatment in 2003 on height increment (Figure 7.3). The incremental growth rate in the fully irrigated I_4 treatment (333 mm) was three times greater than that in the unirrigated I_0 treatment (103 mm).

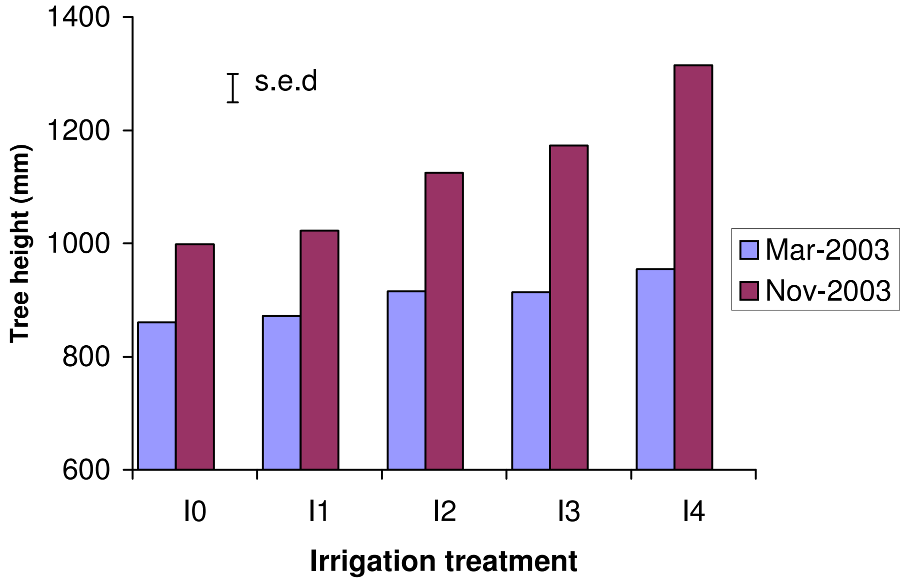
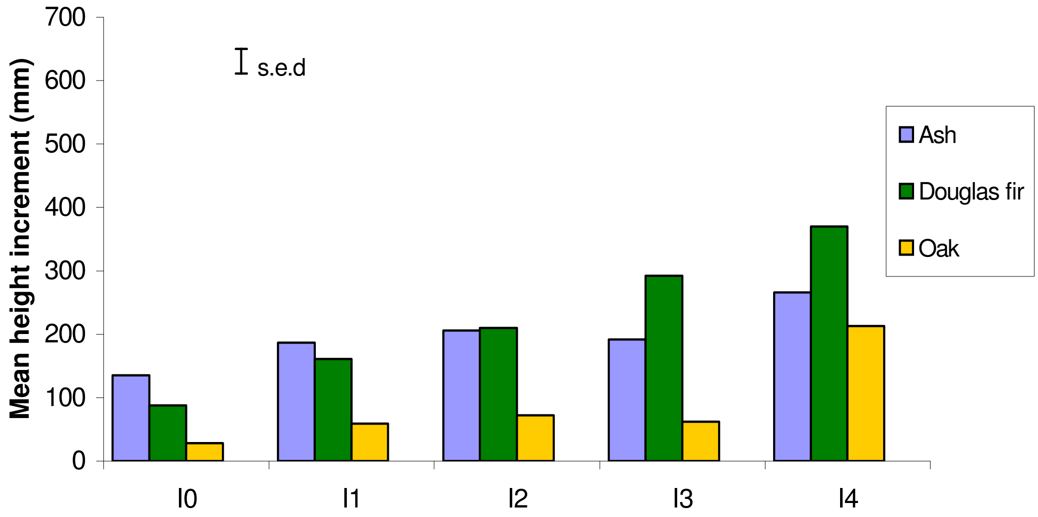


Figure 7.3 Mean height for all three species across five irrigation treatments in March and November 2003.

Ash was consistently the tallest species, with incremental growth rate displaying a similar trend (Table 7.4). The Douglas fir rates under the vegetation treatments were significantly higher than the ash at 224 mm and 197 mm respectively (Figure 7.4). This is also highlighted within the irrigation levels in the vegetation treatments, with Douglas fir showing greater growth rates in the higher water application plots (Figure 7.4). However under the herbicide treatments ash produced the highest incremental growth of the three species. Oak showed the lowest height increment under both the vegetation and herbicide treatments (Figure 7.4).

a) Vegetated



b) Herbicide

Figure 7.4 Differences in incremental growth rates of ash, Douglas fir and oak in a) the vegetated and b) the herbicide plots under five irrigation rates (s.e.d=39; df=4).

7.3.3 Tree diameter

Effect of species and herbicide

In March 2003, prior to diameter summer growth, there were significant effects of species and herbicide on tree diameter. The mean diameter of the ash (17.5 mm) was 29% greater than the oak (12.4 mm) and 32% greater than the Douglas fir (12 mm). The tree diameter in the herbicide treatment (15.1 mm) was 15% greater than that in the vegetation treatment (12.9 mm) (Table 7.4). There was no significant effect of irrigation (P=0.3) and no significant interactions.

Table 7.4 Effect of vegetation treatment on the diameter (mm) of three tree species in March and November 2003, and the diameter increment over the year.

	March 2003			November 2003			Increment		
	Vegetated	Herbicide	Mean	Vegetated	Herbicide	Mean	Vegetated	Herbicide	Mean
Oak	11	14	12.4	14	20	17.2	2.7	5.9	3.9
Ash	16	19	17.5	22	27	24.4	5.7	8.0	6.9
D Fir	11	13	12.0	15	22	18.4	3.3	5.4	4.4
Mean	12.9	15.1		17.0	22.9		3.9	6.4	
s.e.d species mean (d.f.10)			1.03			1.5			0.7
s.e.d vegetation means (d.f. 5)			0.5			0.8			0.2

Eight months later in November 2003, there were effects of species (P<0.01) and herbicide (P<0.001) on tree diameter. The mean diameter of ash (24.4mm) was 25% greater than Douglas fir (18.4mm) and 30% greater than oak (17.2mm) (Table 7.4). The tree diameter in the herbicide treatment (22.9mm) was 26% greater than that of the vegetation treatment (17.0mm). There were no significant interactions.

The height difference in growth over 2003, showed a significant effect of irrigation (P<0.05), species (P<0.05) and herbicide (P<0.01) on tree diameter (Figure 7.5). There were no significant interactions. There was a significant herbicide x irrigation interaction (P<0.05) on the tree diameter increment (Figure 7.5).

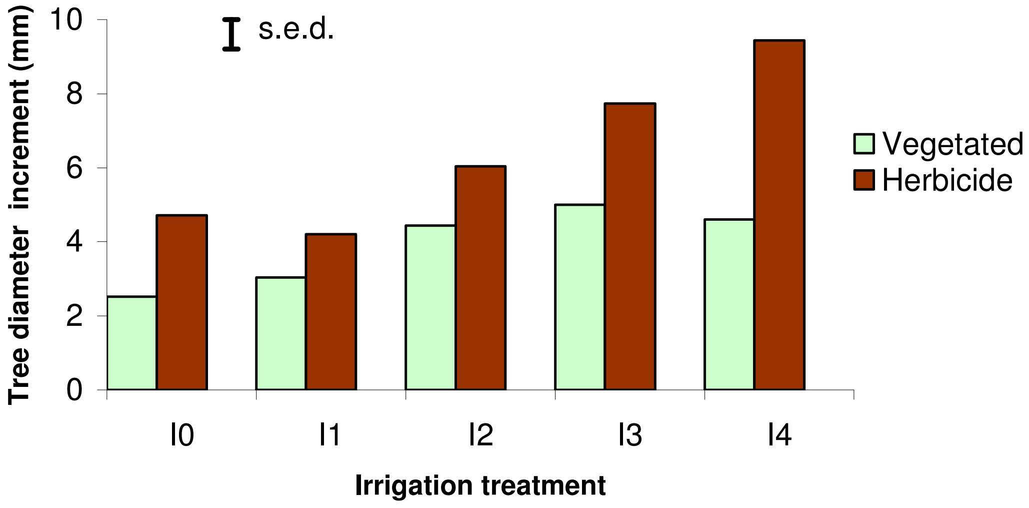


Figure 7.5. Tree diameter increment and irrigation treatments between vegetated and herbicide plots. (s.e.d=0.79; df=5.92).

The relationship between the tree height and diameter was compared for each species. The mean incremental correlation, for height and diameter, between all the irrigation plots and treatments were signification in the Douglas fir (P<0.01) and ash (P<0.01) no relationship was found within the oak (Figure 7.6).

a) Vegetated

b) Herbicide

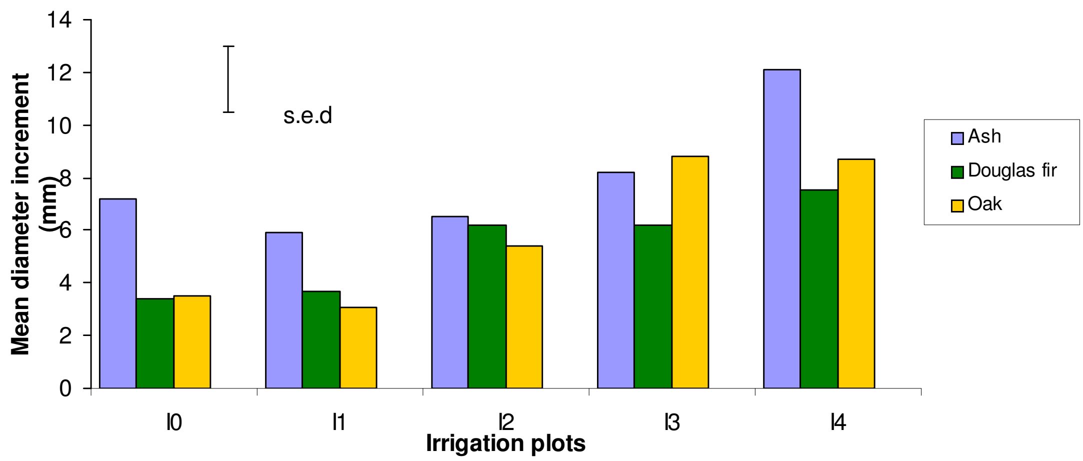
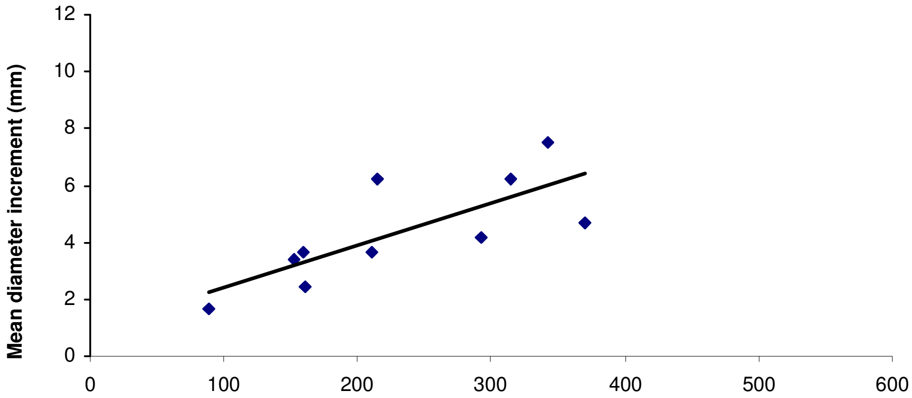


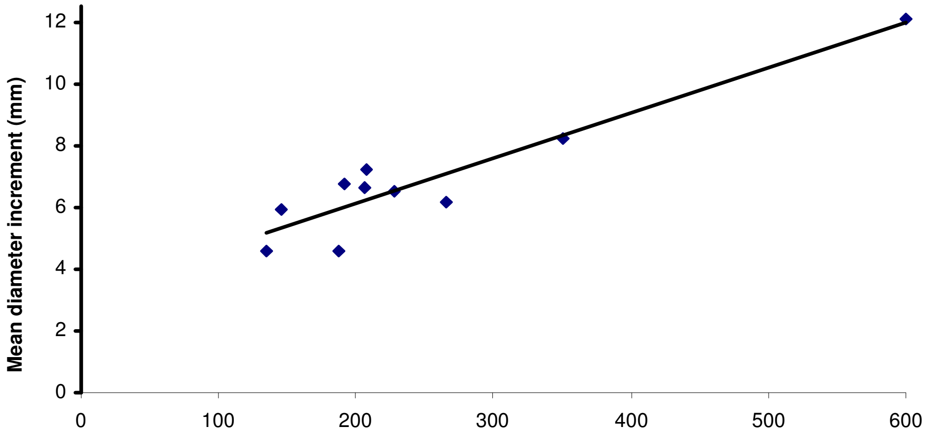
Figure 7.6. Incremental diameter growth of ash, Douglas fir and oak species in a) the vegetated and b) the herbicide treatment during 2003 under five irrigation rates (s.e.d.=2.5; df=20).

The relationship between the height and diameter was evaluated, with both Douglas fir and ash showing a positive correlation rs=0.848 and rs=0.782 respectively (Figure 7.7). Oak showed no relationship between height and diameter with a correlation of rs=0.248 (Figure 7.7).

a) Douglas fir



b) ash



c) oak

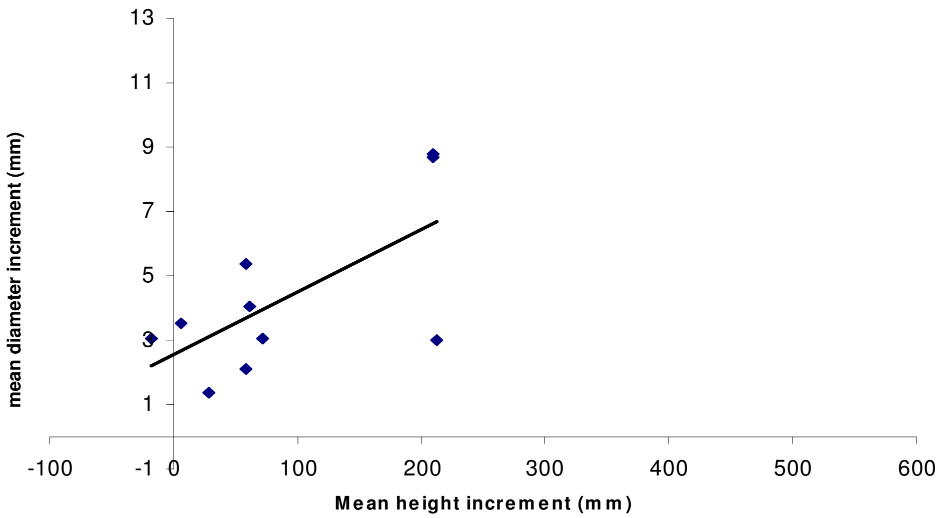


Figure 7.7 Correlation between mean incremental growth rate (height and diameter) of a) Douglas Fir r_s=0.848; b) ash r_s=0.782; c) oak r_s=0.248.

7.3 Discussion

7.3.1 Survival

Tree survival was assessed each year, and also evaluated for the full three years. The vast majority of the ash trees survived throughout the experiment, and those that died were through indirect reasons rather than the imposition of treatments.

Effect of species

As with previous years the survival rates between species was highly variable. Ash showed good resilience with no deaths irrespective of slope position, irrigation or vegetation treatment (Figure 7.1, Table 7.1). High survival rates for ash have also been noted by Groninger *et al* (2004), Kerr and Cahalan (2004), Hofmeister et al. (2004), especially its high tolerance of a range of soil types and conditions (Grimes et al., 1996). Kerr and Cahalan (2004) concluded that ash established well, compared to other broad-leaved species, due to the ability to quickly develop extensive root systems. This was supported by the ability to establish on the sandy conditions of the experimental plots, which are well within the environmental range of ash (Stewart *et al*., 2006).

Douglas fir showed a repeated pattern of high mortality in transplants throughout the experiment. Kozlowski (1987) reported high mortality of transplanted Douglas fir under drought conditions, due to the low root shoot ratios. This maybe associated with high water loss through the needles, especially in bare rooted transplants (Kozlowski, 1987). Douglas fir survival was lower in the herbicide treatment than the vegetated plots (Figure 7.2). However this was primarily the result of one particular plot as reported (Table 7.1). Possible factors that may have caused poor survival in this plot were herbicide application, rabbit damage, or soil water effect. Douglas fir had variable rates of survival, however after the initial year, very few original trees perished.

Herbicide: the effect of herbicide on Douglas fir may have been due to the small initial size of this specimens, however this was also a factor in the other Douglas fir plots, as application followed a standard procedure. The adjacent ash plot showed no adverse effects of herbicide application. Although Britt and Smith (1996) reported that ash is relatively herbicide tolerant, the relative sensitivity of Douglas fir to glyphosate is not known but it was felt this was not the primary factor of the poor survival.

Rabbit damage: rabbit damage may have been associated with herbicide application, in that the neighbouring vegetated Douglas fir plot, in block 1 showed quite high survival and no sign of rabbit damage. Rabbit damage was noticed on the adjacent ash trees under herbicide treatment, (Figure 7.8), and a key reason for their survival may have been the large stem diameter (Table 7.4). Oak displayed minimal rabbit damage. This may have been due to the distance of the oak plots from the area affected, but Grime et al. (1996) reported that oak are less susceptible to attack by rodents due to their toxic and unpleasant taste.

Soil water content: neutron probe readings showed that this area of poor Douglas fir survival was particularly dry in 2001 (Table 6.1). However there is no evidence of this plot being particularly dry under the irrigation treatments applied in 2003, and mortality was still significant in the irrigation plots I_3 and I_4.

Figure 7.8 Rabbit damage, by bark stripping, to an ash in February 2004.

Oak showed an increased survival rate compared to 2001 and 2002 data (Chapter 5). This species displayed a similar trend to the Douglas fir in terms of higher survival in the vegetation plots compared to the herbicide treatments. Irrigation levels supported this increased survival of both Douglas fir and oak. Oak showed poor survival of the original plants throughout the experiment. Some of this can be linked to low water applications in the I_0 and I_1 plots. Although poor establishment in relatively dry conditions would have contributed to this.

7.3.2 Growth

Effect of species

Three years after planting, ash trees were 28-62% taller and 33-41% broader than that of oak and Douglas fir. The superior growth of ash has been reported by Moffat (1999), especially under reduced water supply. Grime *et al*. (1996) suggest that early rapid growth of this species may be dependent on high rainfall in early summer, with the root systems preferring to be above the permanent water table, which is reflective of the experimental site (Chapter 4). Moffat (1999) also suggested that growth rates in ash were likely to be unaffected by reduced water supply. This was certainly the case within the vegetated plots, although individuals in the higher irrigation showed superior growth rates in terms of height and diameter increment (Figures 7.4 & 7.6). Although this was not significant, therefore under ideal conditions performance of this species would be increased. However increases in height and diameter increment were identified in the herbicide plots related to irrigation. There was a strong statistical correlation between incremental height and diameter (Figure 7.7), suggesting that water was a factor in the growth of ash, although this species had excellent survival, water improved the species developmental growth.

Douglas fir, although displaying poor survival rates, showed interesting results in growth towards the experimental treatments. The significant effect of irrigation on Douglas fir showed the greatest height increments of all three species in the vegetated plots, and a strong link to irrigation in the herbicide plots. This species showed the strongest correlation between height and diameter increments (Figure 7.7). Cienciala *et al.,* (1994) highlighted the relationship between relative stem area increment and water availability in trials on Norway spruce (*Picea Abies*). They showed an increase in incremental growth of individuals in irrigated plots. This experiment focused on larger trees and no understorey vegetation (Cienciala et al., 1994), however still showed a correlation of growth of soil water interactions. The Douglas fir in this study displayed the greatest incremental height within all irrigated plots, even in the vegetated plots despite having variable survival levels.

Oak displayed the greatest variation in growth rates of all three species. Incremental height rates were very poor, especially in the herbicide plots (Figure 7.4), showing the lowest height gain. However the height performance increased with water application. Moffat (1999) also provided evidence that growth rates in oak were likely to be greatly affected by reduced water supply, which was supported in this study. As did Fuhrer (1998) when studying oak decline.

Incremental diameter followed a similar pattern in terms of poor growth. However again the higher water application rates improved mean diameter particularly in the herbicide plots (Figure 7.6). There was no correlation between incremental height and diameter due to the high variability of growth patterns throughout the irrigation plots.

One factor may be that transplanted trees can often show preference to increased diameter or leaf area, as a repair mechanism for loss of fine root growth in the transplanting process (Sorensen & Cahalan, 2004). However, Burgess et al. (1996) suggested that stem diameter in pedunculate oak reflected a similar pattern to that of height. Bare root stock may also have been a factor in the survival of this species (Burgess et al., 1996), which can often show poorer survival rates than other species.

Effect of irrigation

Water stress is the most common limitation on tree growth (Kramer, 1987), influencing all phases of tree development (Kozlowski, 1982a). Lof *et al* (2004) identified soil water stress as a possible limiting factor in tree establishment. Irrigation applications over the 2003 growing period had no statistical effect on species survival, although there were increases in the survival of oak and Douglas fir towards the higher applications of water. Most of the mortalities in the oak and Douglas fir occurred early in the season thus the irrigation applications may have started too late to significantly affect survival. Also as suggested by Clarke & Kjelgren, (1990) the use of transplants over the 2002-2003 period to replace previous mortality, may have been more affected by water stress compared to the maturing trees. Magnus *et al.*, (2004) work on transplantation of trees suggested that soil water stress can play a key limiting factor during the establishment phase. This was clearly identified in this study.

The significant effect of irrigation on height showed the importance of water early on in the development of trees and early in the growing season. Each species displayed different growth patterns, but all species mean incremental height development increased with higher water applications (Table 7.4). Water availability in the upper layers of the soil was greatly reduced in the low and non-irrigated plots. Water from deeper layers was highly limited in the experimental site, especially in the higher plot of blocks 1 and 3 and may have restricted the trees access to water.

A number of authors have suggested that ash may be sensitive to moisture stress (Kerr & Cahalan, 2004). Within this study there may be a direct relationship between soil moisture and incremental growth of ash as opposed to links with survival. The ability of ash to tolerate varying environmental perimeters has been highlighted by Stewart *et al.* (2006), identifying the high levels of genetic variation in all ash stands that were sampled. Providing the species with the genetic ability to adapt accordingly to various environmental gradients.

However the availability of water can be related to position on the national scale. Hall & Roberts (1990) examined water use in two English counties (Table 7.5), and suggested that the water use varied to the amount available in the communities. However these were just rough guides in predicting water use and availability.

Table 7.5 Speculative annual water use (Hall & Roberts, 1990).

Annual Rainfall	County	Water use (mm)		
		Conifers	Grass	Deciduous
550	Cambridge	566	529	504
1100	Devon	710	527	570

There is an interesting effect of irrigation rates on tree diameter (Figure 7.6). In plots I_0 and I_1 there was no or very little water application and incremental diameter growth shows no real differences. However tree diameter increased in trees throughout other irrigation plots, with a reduction in diameter in ash and oak species, in I_4.

Effect of Vegetation

The importance of weed control in the successful establishment of trees (Britt & Smith, 1996) has been comprehensively studied, as has grass control for the successful establishment of young plants (Savill, 1992). The greater susceptibility of diameter rather than height to competition for water and nutrients was reported by Burgess *et al.* (2004).

Survival within the bare ground treatments, was showed as highly variable. In this study ash showed the best incremental growth rates throughout all the irrigation plots (Figure 7.4). Kerr& Cahalan (2004) reported that ash growth could be restricted if weed control was poor. This certainly played a factor in this experiment. Groninger *et al* (2004) found that green ash (*Fraxinus pennsylvanica*) was approximately 50-40% greater in the herbicide application treatments compared to the control plots. Similar levels were found in this study with exceptional growth rates in the herbicide plots compared to lower growth rates in the vegetation treatments.

If these findings are related to trees on bare ground plots (Figure 7.5) a very different result can be found. The opposite appears to occur with a reduction in diameter growth in I_1 and a steady diameter increase in the full irrigation plots. Figure 7.7 showed varying correlations with height to diameter ratios, with Douglas fir showing a close relationship between the two. Links to increased diameter growth in the initial establishment stages compared to height has been reported by a range of authors (Costello et al., 2005; Lof *et al.,* 2004).

Incremental height within vegetated and herbicide plots showed consistent variation in growth. In all but one (I_1) irrigation plot, growth rates in the herbicide areas showed the greatest incremental rise (Figure 7.4). The highest water applications were significantly different. This was also reflected in the incremental diameter growth within irrigation plots (Figure 7.6), with trees in the herbicide plots performing better than the vegetated areas. Three years after planting, the trees in the herbicide plots were 17% taller and 35% broader then those in the vegetated treatments.

Magnus *et al.,* (2004) identified that weed control, especially in the growth of oaks, had a positive effect on Height growth in all species. Although the effect of weed control, in this experiment, on establishment was insignificant. It was also reported that without weed control there was a trend towards increased mortality in both beech and oak (Magnus *et al.,* 2004).

7.4 Conclusion

Growth of the trees planted was a product of individuals surviving the initial first year of planting. This allowed (especially in the ash) rapid establishment in both vegetation and herbicide treatments. However, unlike the other two species planted, ash had the ability to adapt to the environmental parameters applied within the experiment. It provided a springboard for subsequent good growth rates. The survival of Douglas fir was affected, in 2003, by the failure of individuals in one plot. The high death rate is rather an anomaly, rather than any direct impact from one particular factor.

Growth in terms of height and diameter fluctuated greatly between species and treatments. Although the extremes of low soil moisture and high ground vegetation cover proved to have the biggest impact on tree growth, under high irrigation levels tree species showed varying degrees of growth. However the general performances were of increased size and width.

8 Ground Vegetation

This chapter describes the ground vegetation measurements made during 2003.

8.1 Background and objective

The objective of the study was to determine the interactions between tree species and floral diversity. This chapter not only assesses the effect of ground vegetation on tree growth, which has largely been reviewed in previous chapters, but also changes in community swards through irrigation and species dominance.

8.2 Methodology

The experimental site is described in Chapter 3. In April 2001, plots 1, 2, 4, 5 and 6 were all seeded with a set-a-side mix consisting of red fescue (*Festuca rubra*) and rye grass (*Lolium perenne*). This provided a standard vegetation cover for the vegetated treatment plots. Plot 3 (due to changes in experimental design) did not get any seed application, and plants were allowed to germinate from the residual seed bank after herbicide application ceased. The collection of vegetation data was restricted to blocks 1 and 2 where irrigation treatments were applied during 2003.

All vegetated plots were surveyed for species presence and abundance in September 2003, after irrigation applications had ceased. Three 0.25 m^2 grided quadrats were randomly placed in each of the five irrigation sub-plots for all the vegetated plots. All plant species within the quadrats were identified and frequency counts were recorded. Plant species diversities were established for each of the irrigation plots, to identify differences in sward community and evenness of plant dominance.

To allow better evaluation of plant data against other environmental variables, it has been transformed into a diversity index using Shannon's Diversity Index, which accounts for both abundance and evenness of the species present.

After plants were identified and recorded all above ground vegetation was harvested, within the quadrats, to ground level and removed. Samples were air dried over a period of four weeks, combining the three quadrats in each irrigation plots. After drying, the dry mass of the samples for each irrigation plot, was recorded.

8.3 Results

Vegetation data was evaluated in relation with irrigation levels applied throughout 2003 (Chapter 6), providing the basis for the evaluation of field data. In total, 23 species were recorded across the experiment (Figure 8.1), of which red fescue and perennial rye grass were seeded (Appendix B). The remaining species have developed from the residual seed bank or have been deposited, within the site, through various mechanical means.

8.3.1 Plant distribution

There was no significant effect of irrigation treatment on the number of species found within the experimental plots. However plot 3 displayed a difference in distribution with a greater number of species towards the reduced irrigation subplots I_1 and I_0 (Figure 8.1). This highlighted the difference in species composition between plot 3 and the other vegetation plots in blocks 1 and 2.

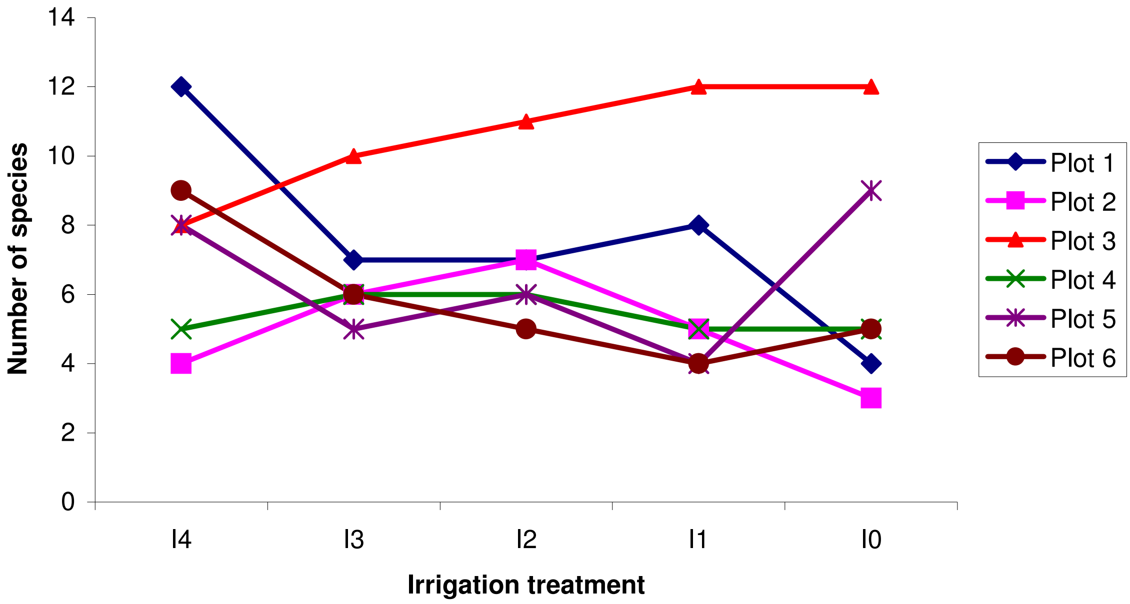


Figure 8.1 Plant species abundance within irrigation plots for all vegetation plots (blocks 1 and 2), including plot 3.

The most abundant species in the majority of plots was red fescue which occupied almost 100% of the quadrat area in plots 1, 2 and 6. By contrast other grasses such as bents (*Agrostis* spp) and perennial ryegrass (*Lolium perenne*) were more abundant in plots 4 and 5, where the fescue occupied a more sub-dominant role. In plot 3, which was not seeded, the distribution showed a much more diverse ruderal community, with no particular species or sub-plot being dominant (Figure 8.1).

8.3.2 Biomass

Irrigation had a significant effect on the harvest of biomass ($P<0.01$). Biomass results were higher in zone I_4 where most irrigation was applied and reduced to a minimum in zone I_0 where no irrigation was applied (Figure 8.2). Plot 3 showed the highest biomass weights, where the ruderal community had a taller vegetation cover.

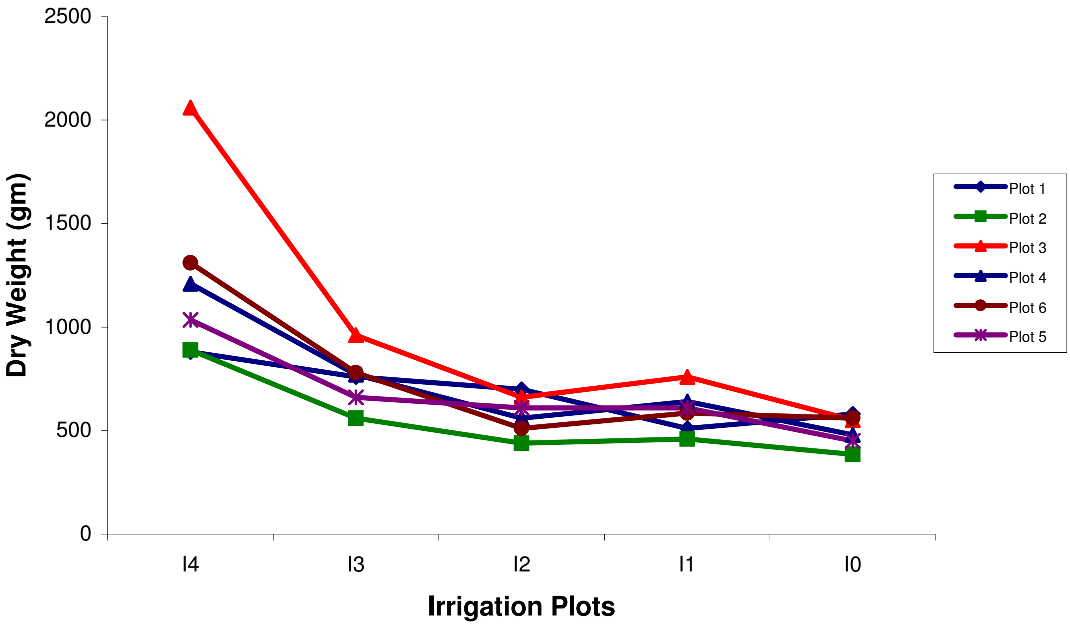


Figure 8.2 Differences in dry weight between irrigation treatments (I4-I0) and the six vegetation plots. Plots 1, 2, 4, 5, 6 seeded during the establishment stage, plot 3, dominated by tall ruderal species.

8.3.3 Correlation between diversity and irrigation

Pearson correlation coefficients for all of the measured factors showed positive correlations between tree height and diversity and that irrigation levels had a significant effect on biomass (Table 8.1). There is a strong association between mean tree height and the diversity of the plot (Figure 8.3). This data looked at all trees irrespective of species, plot position or irrigation subplot.

Table 8.1 Pearson correlation coefficient results between Diversity, biomass, irrigation and mean tree height a) shows a positive correlation between tree height and diversity and b) a positive correlation between irrigation and biomass.

	Mean Tree Height	Diversity	Biomass
Diversity	**0.695**[a]		
Biomass	0.551	0.222	
Irrigation	0.296	0.074	**0.722**[b]

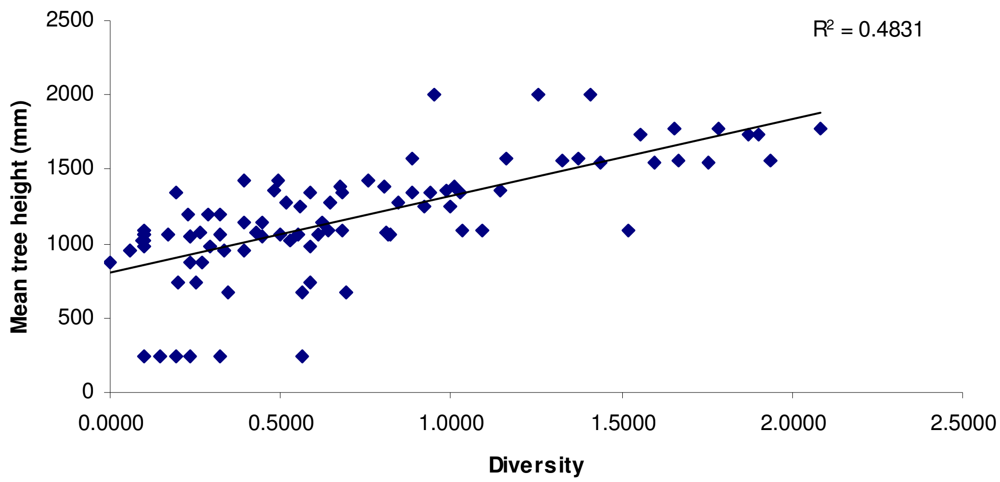


Figure 8.3 Association between diversity and mean tree height. Showing that increases in plant diversity were associated with increases in tree height.

There was a significant relationship between the mean festuca abundance and plot position, excluding plot 3 (p<0.05). Dominance was highest in plot six (Appendix C).

The abundance of festuca had a significant effect on species diversity within the grassland sward. As abundance of fescue increased plant diversity decreased (Figure 8.4).

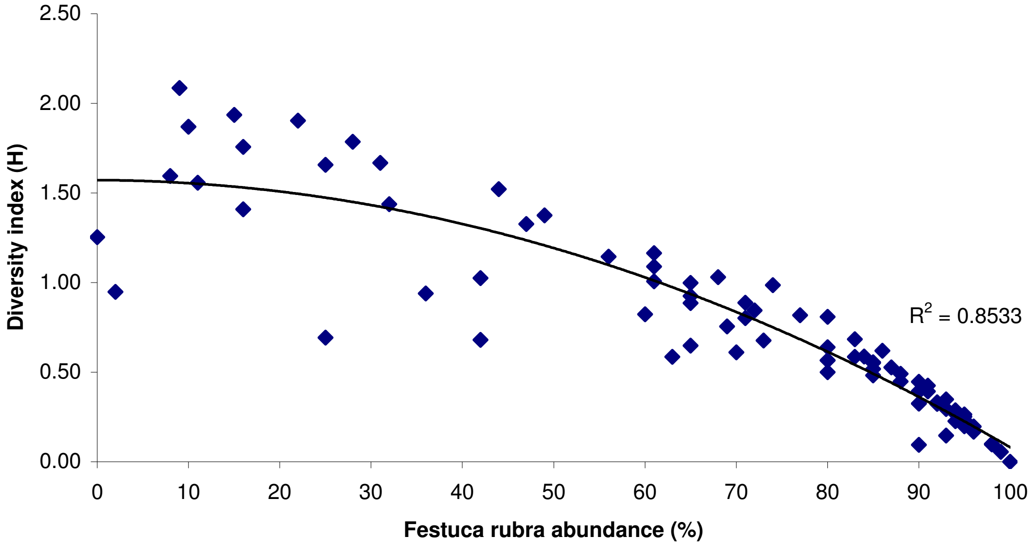


Figure 8.4 Relationship between floral diversity and abundance of *Festuca rubra*. Highlighting the decrease in plant diversity with the increase in fescue abundance.

8.4 Discussion

Plant distribution

Festuca appears to be a controlling factor within the sward. Analysis showed a dramatic decline in diversity with an increase dominance of fescue (Figure 8.4). This was not restricted to particular irrigation plots showing a consistency throughout all water application levels. However increased SWD may have improved this species dominance, certainly increased biomass was a result of greater fescue growth in plots I_4 and I_3.

Studies such as Smith *et al*, (2002) have tried to quantify the effect that vegetation has on tree growth. This research showed that a vegetation free circle around the base of the tree improved diameter growth in the fist year and height growth in subsequent years. This work also identified possible links with allelopathic effects from fescue species. Grimes *et a.l* (1989) and Glenn-lewin *et al.* (1992) both identified that species distribution was controlled by particular factors or stages in successional development. The seeding of vegetation plots has created artificial seres in the vegetation communities. With grass dominated swards compressing ruderal species establishment (Hooley & Cohn, 2003) which was found on the bare ground in plot 3.

Biomass

The relationship between biomass and floristic diversity is unclear (Woodard, 1990). Experimental evidence that plant species diversity has a positive effect on biomass production appears to conflict with what is found in natural communities (Fridley, 2002). Certainly plot 3, in this experiment, produced the greatest amount of dry material, this in turn had the greatest diversity and greatest height of all plots. As mentioned the seeding of the vegetation plots had created an artificial sward and therefore would not follow natural successional sequences.

Biomass was increased by water availability within the experiment. As with similar studies (Cienciala, *et al*. 1994; Britt, 1999; Groninger *et al*. 2004) water availability promotes the development of both tree and ground species. However if high levels of soil moisture are available ground vegetation may not necessary impact on tree growth (Britt, 1999). Although the amount of above ground vegetation in the plots I_4 and I_3 was lower than that of I_0 and I_1, under this scenario the impact on tree growth would have been greater.

Diversity

The results confirm the pattern seen in Figure 8.1. Plots 1, 2 and 6 show no significant difference with plots 4 and 5 show no significant difference. All the plots show a significant difference with plot 3. The difference between plots 4 and 5 and the others is not easy to account for, as the treatments applied were similar to plots 1, 2, and 6. It could be that there is a naturally wide variation in diversity and that the significance level of 95% is too sensitive. However the difference between plot 3 and the others is worth examining, as there is a difference in treatment, which may be having an effect. All the plots were seeded with fescue/bent except plot 3. The fescue dominance when related to diversity would suggest to have a decreasing effect on the presence of other species (Figure 8.4).

Based on the work of Grime (1989) the autecology of the 23 species in the floristic survey shows that 19 have some association with arable land, while two, white campion (*Silene latifolia*) and strawberry (*Fragaria vesca*), are not normally associated with this environment. White campion is frequently found on disturbed land (Grime *et al.*, 1989) and would have developed quickly after establishment of the experimental site. The strawberry is probably a remnant of the "pick your own" activities practised on this field many years ago. Unrecorded observations of the flora in the area surrounding the experimental field found a more diverse vegetation with forb species and grasses not present in any of the experimental plots. The evidence suggests that the species present are not the result of colonisation, but a community that is re-emerging after the cessation of disturbance by agricultural treatment.

On sites that were previously vegetated, seed banks play an important role in re-establishment (Glenn-lewin *et al.*, 1992). Colonisation is less likely to occur because of isolation from possible seed sources, and competition from vegetation remaining from the previous land use (Hooley & Cohn 2003). The area around the experimental field was mown at regular intervals throughout the life of the experiment, a practice which is known to encourage the growth of forbs and maintain variation in sward. The grass growing in the experimental plots was unmown and, again, unrecorded observations of the plots show that the fescue sward formed a thick cover over the whole area where it was growing, creating high competition stress, which would deprive emerging species reducing light and moisture availability (Groninger *et al.*, 2004).

Grime *et al.* (1989) records that fescue is a gregarious grass normally associated with diverse communities and does not tend to dominate in the natural environment, although it does have the capability of forming stands. It is equally likely that any grass species left unmown could have caused the same effect.

Some *Festuca* spp. are known to be allelopathic. In particular, *Festuca rubra* is known to chemically inhibit the growth of forsythia, and tall fescue is known to inhibit the growth of pecan trees (Smith, Cheary & Carroll, 2001). The allelopathic nature has only been reported in specific species of plant, but it is possible that the effect is more general than is reported (Smith *et al*., 2002). The correlation between mean tree height and diversity shown in Figure 8.3, could be evidence of the dense fescue sward preventing water reaching the ground, limiting the supply of nutrients to the tree roots, or of the allelopathic effect.

8.5 Conclusions

Irrigation significantly increased the biomass of the ground flora found in the vegetation plots in blocks 1 and 2, with greater dry matter in heavily irrigated plots. Diversity for all plots within the experiment, except plot 3, was generally low, especially if compared to the surrounding grass area. This was due to the seeding of plots after tree planting.

In the seeded plots the presence of red fescue reduced the sward diversity. The dense fescue sward may have prevented emergent growth by shading the ground from light and water. The allelopathic properties of the fescue may be chemically inhibiting the development of competitors in the plots where the species is dominant. The correlation between tree height and diversity may be due to either of these theories, however more specific recording of interactions would be needed to support them.

The results support the view that ground flora management is influential in the development of early tree growth and that ground vegetation control will improve the success rates of trees in establishment and developmental stages. However under the right soil moisture conditions this competition may be reduced.

9 Synthesis

The stated aim of the research was to improve our understanding of the interactions between water availability and the development of new woodlands from a production, ecological and recreation perspective. It focussed on the traditional plantation crops of ash, Douglas fir and oak. It also focused on the interrelationships between the tree species and the understorey vegetation, both in terms of production and conservation value. The specific objectives were:

1. To determine the responses of oak (*Quercus petraea*), ash (*Fraxinus excelsior*) and Douglas fir (*Pseudotsuga menziesii*) to water availability.
2. To determine the responses of oak, ash and Douglas fir to the removal of competing vegetation.
3. To determine the interactions between the above.
4. To determine the interactions between tree species and floral diversity.

The objectives of this research were to determine the responses of ash, Douglas fir, and oak to water availability and removal of competing vegetation. In addition the effect of tree species on floral diversity was determined. This chapter briefly synthesises the results and reviews the experimental process as a whole and tries to draw the different strains of this applied research together.

9.1 Response of species and water availability

Irrigation during 2003 made a significant effect on the soil water deficits between subplots. Improving growth rates of all tree species in both the bare ground and vegetation plots, where applied in adequate levels, especially for ash and Douglas fir that showed the highest incremental growth. The application of water during this season provided clear differences between irrigation subplots, therefore providing data to assess tree specie's responses.

Although no direct root analysis was taken, the utilisation of below ground water would have direct impacts on the availability of soil moisture. Under the irrigation measure implemented in 2003, water applied was able to penetrate deeper into the soil profile. This would have allowed greater competition by tree species with ground vegetation, which is highlighted in the significant results found during this season.

Ash survival was very good throughout the experiment with only minimal death rates throughout years. Douglas fir and oak showed a repeated pattern of mortality with replant establishment being poor. Very few of any species died from the original tree planting. Mortality was almost exclusive to individuals that were planted as replacements each year.

The three species, used within this research, have responded differently to the treatments imposed. Providing the opportunity to consider their roles in further planting schemes within the midland region. Ash will be a significant species in both natural and plantation woodlands, with its good response to all levels of water availability. This is highlighted by the natural regeneration of this species across Northamptonshire. Oak was significantly affected by drought conditions, especially in the early establishment stage. Although sessile oak is not a prominent naturally occurring species in the midlands, it may be a species that is selected for site on base rich soils. Douglas fir has traditionally limited distribution on the Northamptonshire region, due to the soils and climatic conditions, it is very unlikely that this will change with the predicted drying and warming of the climate. However this species provided an interesting insight into how plantation conifers may develop under these conditions.

Understanding the effect of soil water holding capacity on the growth of individual species would enable better site and species selection, and more accurate estimates of future yields. An estimation of the maximum rates of water use by trees will allow woodland designers to calculate the numbers of potential species applicable to site or locations around the British Isles.

This research would suggest that large-scale application of water to tree plantations is largely unrealistic in terms of costs and human resources. Therefore there is an increased need for good site/species selection, which as Merryweather (2007) suggests is not often the case. This certainly will need to be the case as climatic change projections are suggested to make natural or artificial development of woodlands increasingly problematical (Ledig & Kitzmiller, 1991). It would seem highly likely that water availability (rainfall) as well as temperature will have key constraints on growth within the natural growth periods on the east midlands. Greater consideration of species (Hopkins, 2007), their long-term suitability for specific regions and individual sites is required, and is therefore needed to maintain continued woodland development in the region.

9.2 Response of species to competing vegetation

Ground vegetation showed an affect on tree growth, with trees species showing a decline in height and diameter growth in all vegetated plots. However the incremental high of Douglas fir showed an increase related to irrigation. Vegetation also had an affect on survival in oak and Douglas fir. In the initial stages of tree establishment control of vegetation provided significant improvement in survival and growth that was in line with many other studies in this area.

The changes in ground vegetation throughout blocks 1 and 2 highlighted some significant trends in plant competition. The seeding of vegetation plots with rye grass and red fescue reduced the height and species diversity of the sward and biomass. There seems to be few studies that have evaluated the impact of different types of ground vegetation on tree growth. The dominance of red fescue showed a significant effect on other ground vegetation species, especially the ruderal community, to what extent this species impacted on tree growth has not been researched in this study.

Soil fertility was identified as being consistent across the experimental plots, and therefore is unlikely to have had a significant effect on the total biomass from individual plots. The variation of species composition, on biomass, especially between seeded and unseeded plots showed the most significant differences. With the ruderal community producing more above ground biological material.

The consideration of competing vegetation on the establishment of trees will be a significant criterion, within a changing climatic environment. This has been highlighted by many authors, suggesting that higher CO_2 levels and lowering precipitation, will make the impact of uncontrolled ground vegetation a major factor in tree survival and development (Andalo *et al* , 2005; Bodin & Wiman, 2007).

There is an assumption that local provenance seed will be better adapted to planting in adjacent sites (Stewart *et al*, 2006). However the predictions of climate change would assume that, even for a species such as ash, the rate of environmental change could potentially be too rapid for natural variation to develop along similar time scales. Therefore there may be a case to plant more southerly province seeds and seedlings to allow higher survival rates for the years to come. This was a factor highlighted by Ledig & Kitzmiller (1991), more than a decade ago, suggesting that reforestation strategies should focus on the broader deployment of species, seed sources and families, to combat climate change.

The idea that ash has reduced in importance within European ecosystems has often been linked to anthropogenic factors of management (Hofmeister *et al*, 2004), however with the decline of traditional management systems, a significant increase in the nitrogen balance has occurred (Hofmeister *et al*, 2004). This coupled with the lack of consistent management has seen a revival of ash as a major woodland component. This study has highlighted possible limiting effect of reduced water availability on early tree development. The work has highlighted the importance of water availability in early development in terms of limited survival (early development) and limited growth (early season). In light of climate change research the projections would suggest that these weather patterns could become more extreme. Therefore these issues must be part of the decision making process for woodland planting.

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Appendix A Statistical analysis of data using a blocked ANOVA design.

Table A.1 Statistical analysis of growth data using Genstat (April 2001-April 2002)

```
scalar nb,ni,ns,nh;4,5,3,2
units [120]
fact [levels=#nb;labels=!t(block1,block2,block3,block4); valu=5(1,2,3,4)6] block
fact [levels=10;labels=!t(I0L,I1L,I2L,I3L,I4L,I4R,I3R,I2R,I1R,I0R); \
valu=(1...10)12] irrside
fact [levels=#ni;labels=!t(I0,I1,I2,I3,I4); valu=(1,2,3,4,5,5,4,3,2,1)12] irrigation
fact [levels=#ns;labels=!t(Oak,Ash,Douglas);\
valu=5(2,1,2,1,3,1,3,1,3,2,1,2,1,3,2,3,2,2,1,3,1,3,3,2)] species
fact [levels=#nh;labels=!t(vegetation,herbicide);\
valu=5(2,1,1,2,2,2,2,1,1,2,1,2,2,2,2,2,1,1,2,1,1,1,1,1)]herbicid
"variate [valu=(0,4.5,9,13.5,18,22.5,27,31.5,36,40.5,45)12] dist
covariate dist"
read height
5 5 5 5 5 6 6 6 6 6 7 7 7 7 7 8 8 4 8 8
5 5 5 5 5 6 6 6 6 6 7 7 7 7 7 8 8 2 8 8
5 5 5 5 5 6 6 6 6 6 7 7 7 7 7 8 8 9 8 8
5 5 5 5 5 6 6 6 6 6 7 7 7 7 7 8 8 8 8 8
5 5 5 5 5 6 6 6 6 6 7 7 7 7 7 8 8 5 8 8
5 5 5 5 5 6 6 6 6 6 7 7 7 7 7 8 8 9 8 8:
block block/irrigation/(species*herbicid)
trea species*irrigation*herbicid
tabulate [class=irrigation,species,herbicid;print=means] height
anova [fact=3;pfact=3;prin=aov,mi,me,%cv,cov,cont; \
fprob=Y] height;fit=f;res=r
stop
```

Table A.2 Changed statistical analysis of growth data using Genstat (April 2002- February 2003).

```
units [120]
fact [levels=4;labels=!t(Block1,Block2,Block3,Block4);valu=30(1,2,3,4)] newblock
fact [levels=5;labels=!t(I0,I1,I2,I3,I4);valu=(1,2,3,4,5,5,4,3,2,1)12] irrigation
fact[levels=3;labels=!t(Oak,Ash,Douglas);
valu=5(2,1,3,1,3,2,1,3,2,2,1,3,2,1,3,3,1,2,2,3,1,1,3,2)] newspec
fact[levels=2;labels=!t(Vegetation,Herbicide);valu=5(2,1,2,2,1,1,2,2,1,2,1,1,1,2,2,1,1,2
,2,2,2,1,1,1)] newherb
block newblock/irrigation/(newspec*newherb)
treatment newspec*irrigation*newherb
anova [fact=3;pfact=3;prin=aov,mi,me,%cv,cov,cont;fprob=Y] sur2002;fit=f;res=r
stop
```

Table A.3 ANOVA table of tree species survival versus plot position within the experimental blocks in 2001.

Analysis of Variance for Ash survival vv plot position

Source	DF	SS	MS	F	P
Plot pos	7	4.775	0.682	4.20	0.002
Error	32	5.200	0.162		
Total	39	9.975			

Analysis of Variance for Oak survival vv plot position

Source	DF	SS	MS	F	P
C4	7	785.10	112.16	31.48	0.000
Error	32	114.00	3.56		
Total	39	899.10			

Analysis of Variance for Douglas fir survival vv plot position

Source	DF	SS	MS	F	P
Plot pos	7	483.10	69.01	20.76	0.000
Error	32	106.40	3.32		
Total	39	589.50			

Table A.4 ANOVA table of tree species mean height difference versus plot position within the experimental blocks.

Analysis of Variance for mean height of ash vv plot position

Source	DF	SS	MS	F	P
Plot pos	7	13033	1862	1.13	0.370
Error	32	52788	1650		
Total	39	65821			

Analysis of Variance for mean height of oak vv plot position

Source	DF	SS	MS	F	P
Plot pos	7	99645	14235	2.97	0.016
Error	32	153371	4793		
Total	39	253016			

Analysis of Variance for mean height of Douglas fir vv plot position

Source	DF	SS	MS	F	P
Plot pos	7	74758	10680	8.46	0.000
Error	32	40393	1262		
Total	39	115151			

Appendix B plant species and abundance in vegetation plots in blocks 1 and 2.

Irrigation subplot	Quadrat code	*Festuca rubra*	*Trifolium Repens*	*Geranium molle*	*Urtica doica*	*Senecio vulgaris*	*Ranunculus repens*	*Taraxacum officinale agg*	*Lolium perenne*	*Agrostis canina*	*Sonchus asper*	*Cirsium vulgare*	*Holcus lanatus*	*Fragaria vesca*	*Cirsium arvense*	*Epilobium augustifolium*	*Senecio jacobaea*	*Silene latifolia*	*Rumex obtusifolius*	*Plantago lanceolata*	Cerastium holosteoides	*Polygonum aviculare*	*Dactylis glomerata*
	114	95	2	1	1	1																	
	214	91	2				3	2	2														
I4	314	80	2								5	3	6	4									
	413	85												2	10	3							
	513	80													20								
I3	613	77	8						10					2			3						
	712	68							4						7		15	6					
	812	83							6							5	3		3				
I2	912	98															2						
	1011	98											2										
	1111	63				2							1			1				2	1		
I1	1211	93						2											5				
	1310	87				3					5			5									
	1410	90																					
I0	1510	98									2												
	124	98						2															
	224	70	30																				
I4	324	60	35												5								
	423	95	2					1							2								
	523	83	2					1					2		2				5				
I3	623	95											5										
	722	80	18											2									
	822	25	25																				
I2	922	93		2		1				2					2								
	1021	96	2																2				
	1121	93									2												
I1	1221	98								2													
I0	1320	95	3							2													

	1420	80	2					18										
	1520	90						10										
	134	2	3				15				70		10					
	234		5				16				60			7	12			
I4	334	16	2		9						48		25					
	433	11	16				20				23				30			
	533	10	14				27				24		5	20				
I3	633	22	10				27	5			9	7		15				
	732	9				10	20		7		5	15		19	10	5		
	832	28	13	8			8				4	23			16			
I2	932	25					10		8		7	27		23				
	1031	32				2	26							32		3	1	
	1131	16				2	8	11			14	17			32			
I1	1231	8	15				26				2	32		19				
	1330	31	15				18					7		2	24		3	
	1430	47				2	21				13	17						
I0	1530	15	7				16	25			9		8	3				
	144	65	15				20											
	244	84					3	10							3			
I4	344	96						2							2			
	443	85						13					2					
	543	56	7		8			27							2			
I3	643	74	6					12					8					
	742	90			4										6			
	842	88	5					5					2					
I2	942	69	5					26										
	1041	73				3		24										
	1141	71						16							13			
I1	1241	61			6			26							7			
	1340	36						56		2		6						
	1440	42						58										
I0	1540	42						45		12								
	154	61	17								10	8						4
	254	49	23		4						3		15		6			
I4	354	71	10		4						15							
	453	72						17					3					8
	553	85						10			5							
I3	653	65						35										

	752	85								8							1		6				
	852	65								5						15			15				
I2	952	65								25					6	4							
	1051	94															6						
	1151	94							2	3							1						
I1	1251	90								10													
	1350	61	8					2		23			6										
	1450	44	20	5					2	17												10	2
I0	1550	80	10							10													
	164	90	5									2					1	2					
	264	90	5		5																		
I4	364	86	3				2	5			2						2						
	463	95	3							2													
	563	88	5								7												
I3	663	95					3									2							
	762	92												5					3				
	862	91	5													2			2				
I2	962	99	1																				
	1061	98															2						
	1161	92														2	6						
I1	1261	96				4																	
	1360	95								2									3				
	1460	100																					
I0	1560	94	3				3																

Appendix C Statistical analysis of festuca abundance within vegetation plots.

Mean abundance of *Festuca rubra* and plot position (excluding Plot 3)

```
Source      DF        SS        MS        F        P
Plot         4      2667       667     6.54    0.002
Error       20      2039       102
Total       24      4706
                                    Individual 95% CIs For Mean
                                    Based on Pooled StDev
Plot         N      Mean     StDev  ---+---------+---------+---------+-
--
1            5     85.73      4.42               (-----*-----)
2            5     83.40     12.14             (------*-----)
4            5     68.80     17.22    (-----*-----)
5            5     66.40      6.10  (-----*------)
6            5     93.40      2.99                    (-----*------)
                                    ---+---------+---------+---------+-
--
Pooled StDev =     10.10              60        75        90       105
```